CR-183730   P-134

Aerojet TechSystems

Liquid Hydrogen Turbopump ALS Advanced Development Program

Contract NAS 8-37593
Monthly Progress Report No. KGC4-M-2

Prepared For:
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

Date of general release 07-91

(NASA-CR-183730) ALS LIQUID HYDROGEN TURBOPUMP: ADVANCED DEVELOPMENT PROGRAM Monthly Progress Report, 20 May - 23 Jun. 1989 (Aerojet TechSystems Co.) 134 p   N91-26196
CSCL 21H G3/20   Unclas 0019695

Report No. KGC4-M-2

21 July 1989

LIQUID HYDROGEN TURBOPUMP
ALS
ADVANCED DEVELOPMENT PROGRAM

Contract NAS 8-37593

Monthly Progress Report, DR-03

20 May - 23 June 1989

Prepared For:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

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1.0 INTRODUCTION

This is the second, June 1989, Monthly Progress Report submitted as Data Requirement (DR)-03 of the Advanced Launch System (ALS) Liquid Hydrogen Turbopump Advanced Development Program. This program is being conducted by Aerojet TechSystems (AT) for the Marshall Space Flight Center (MSFC), National Aeronautics and Space Administration (NASA), under Contract No. NAS 8-37593.

This activity is defined in the Technical Implementation Plan, DR-15. It is designed to deliver and support two reliable, low cost, maintainable LH_2 turbopumps together with Ground Support Equipment (GSE) and Special Test Equipment (STE) packages to Stennis Space Center (SSC) for testing. One turbopump will be heavily instrumented and cold gas tested to measure the internal pump and turbine environments, the second turbopump will be flight type and hot fired. A key additional deliverable will be the LH_2 Turbopump Cost Model, which will be calibrated with actual hardware fabrication costs and with data from simulated launch support and production acceptance activities performed at SSC during the test period.

Cost and reliability studies, trades, and tests will be performed. Cost reduction and/or reliability enhancing technologies will be substantiated by the design, fabrication, and test of experimental and demonstration hardware.

The program covers a 40-month period of performance and is structured in two phases:

Phase I (12 mths) - Preliminary design and cost model development

Phase II (28 mths) - Detail design, fab., and full scale demonstration

The program is designed around the Work Breakdown Structure (WBS) shown in Figure 1.

This second month effort can be characterized as one of evolving activity from detail planning into the start of major long lead efforts involved with turbopump design and supporting experimental work.

ALS LIQUID HYDROGEN TURBOPUMP
Work Breakdown Structure (WBS)

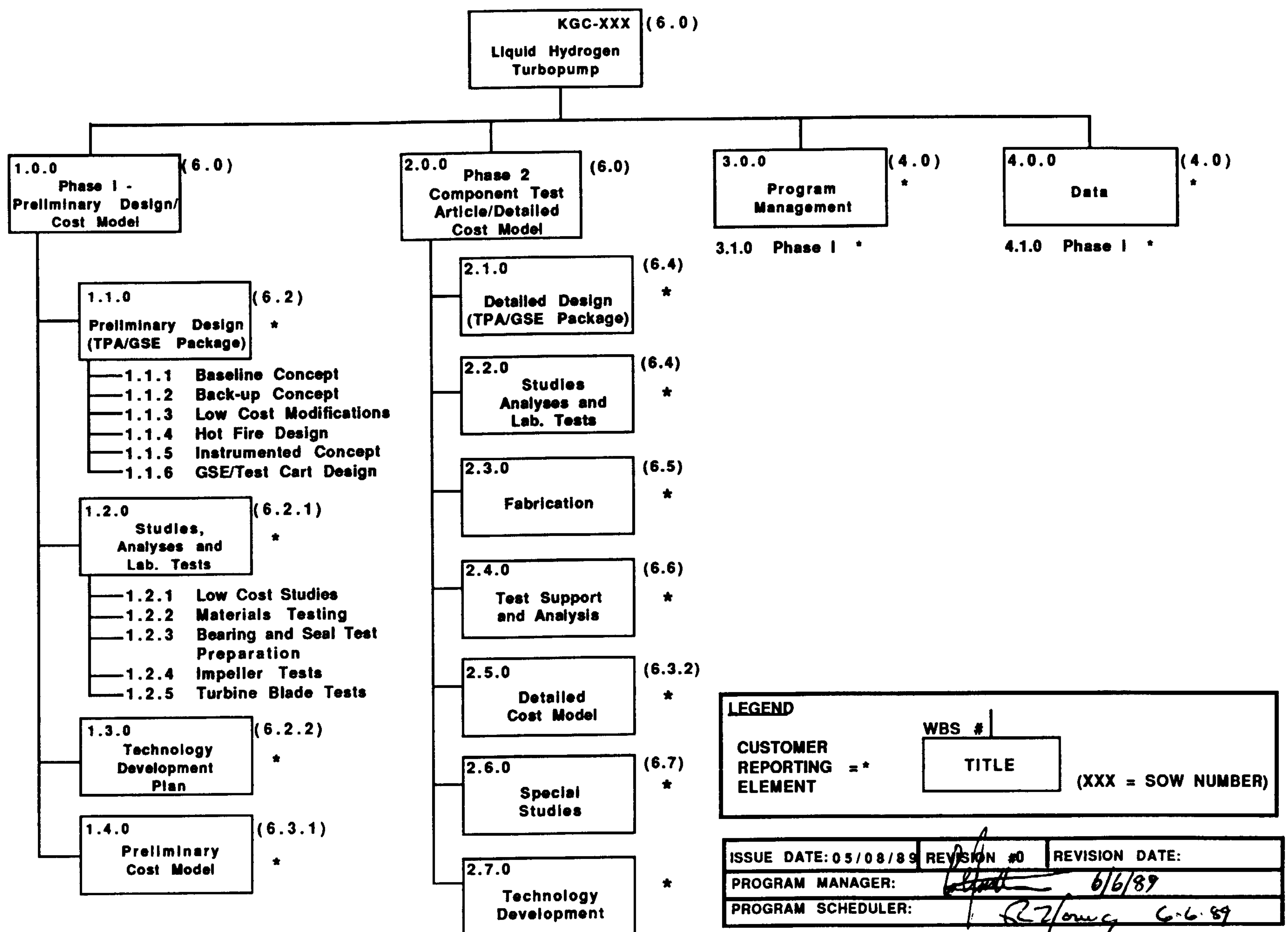

Figure 1. Work Breakdown Structure (WBS)

2.0 SUMMARY

2.1 SIGNIFICANT ACCOMPLISHMENTS

WBS 1.1.1 - The point of departure (POD) turbopump concept was reviewed and finalized during the report period (Figure 2). The basis for the POD was the configuration presented in the Aerojet proposal. After reviewing this proposal concept, several modifications were made. These modifications are outlined below with brief comments on the logic for incorporating them:

a. The dual pump discharge arrangement was changed to a single discharge. The complexity of extra ducting, and flex joints was not justifiable in the STME/STBE engine system. Radial loads resulting from the unsymmetrical pressure gradients are felt to be manageable with the single-discharge, double tongue configuration selected.

b. Commonality of the turbine inlet manifold with the ALS LOX TPA was dropped for this program. The reason was to avoid the inevitable delays which would be experienced in attempting to attain commonality with another contractor's configuration, which is also in a conceptual phase and subject to change. The turbine inlet will be sized specifically for the LH_2 TPA, and will be reduced in size as a consequence.

c. The turbine housing flange arrangement was improved by relocating it away from the first stage nozzles. The large thermal mass, previously in close proximity to the thin nozzle trailing edges, posed a potential cracking problem due to differential thermal expansion.

d. A 10% head margin (5% diameter increase) was built into the impeller design to ensure meeting the required discharge pressure without the need for increasing speed.

e. A 10% turbine power margin was imposed, to be obtained by increasing turbine inlet pressure if required. The impact is a 10% higher design pressure for the turbine inlet manifold and the gas generator.

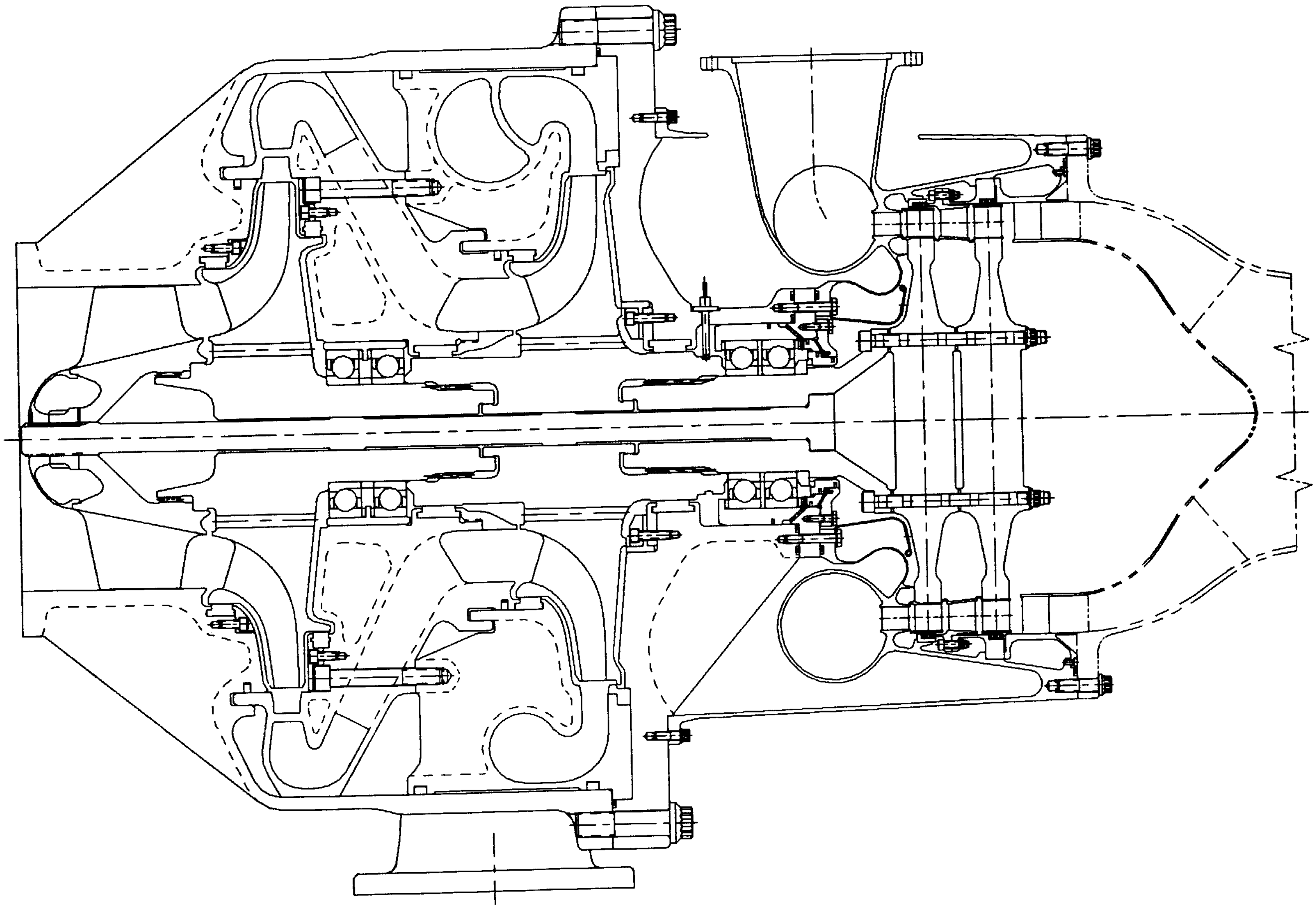

Figure 2. Turbopump POD Design Configuration

f. The backup concept, as an alternative to the use of cast impellers, will now incorporate forged/machined shrouded impellers, rather than the unshrouded type originally planned.

Extensive discussions were held with Mechanical Technology Inc. (MTI) on definitization of the scope and cost of their planned participation in the program. MTI will support the program in the areas of bearing/seal analysis and tradeoffs, bearing materials tests, lift-off seal design, instrumentation and test planning. It is anticipated that the MTI effort will commence during the July reporting period.

A meeting was held at Aerojet during the report period with NASA-SSC personnel. A productive discussion of instrumentation and test requirements took place at this session.

<u>WBS 1.1.6</u> - Conceptual design of the test cart for LH_2 turbopump tests was initiated. Use of off-the-shelf hardware for this unit is being emphasized to minimize cost.

<u>WBS 1.2.2</u> - Discussions were initiated with candidate test laboratories for performing materials tests on existing PCC-supplied cast Ti-5A1, 2.5Sn test bars.

<u>WBS 1.2.4</u> - Procurement activity on the cast titanium impellers intensified during the report period. A CAD package (Figure 3) was completed defining a "typical" cast titanium impeller suitable for feasibility testing. The design is as close to the final LH_2 ADP turbopump impeller design as is possible at this stage in the program. Responses were received from all solicited suppliers and viable candidates were identified. The responses indicated a potential schedule problem in this area. This is being worked at present, and is discussed further in Section 3.0 of this report.

<u>WBS 3.1.0</u> - A program kick-off meeting was conducted at MSFC on 8 June 1989. A copy of the presentation package is included in this monthly progress report (Attachment 1) for record purposes.

On 9 June 1989 a test facility interface meeting was held at MSFC with Stennis Space Center (SSC) personnel in attendance. Requirements for LH_2 TPA

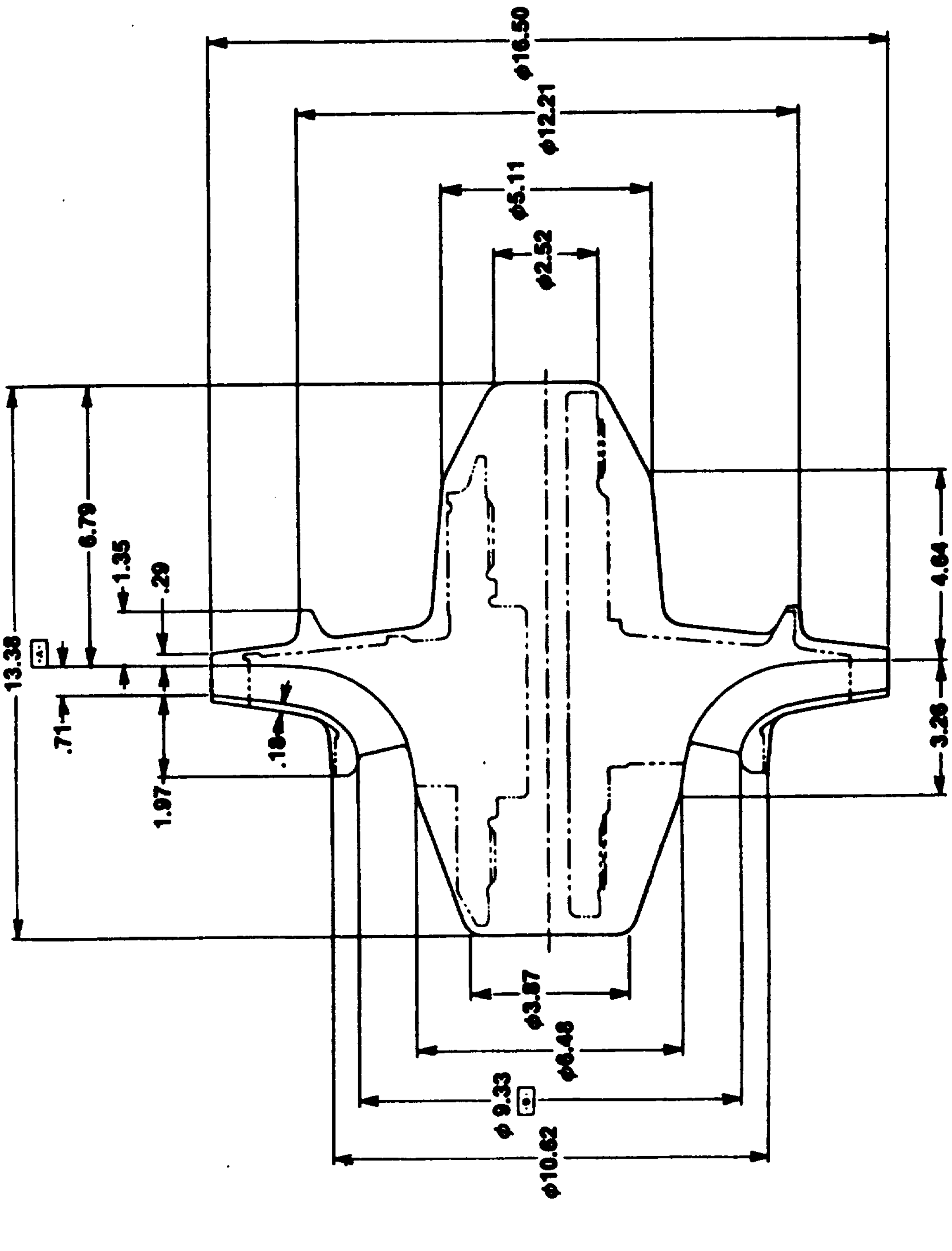

Figure 3. Casting CAD Drawing for Titanium Impeller

testing were discussed, a tentative schedule for future meetings was established, and action items were assigned.

Aerojet worked on two action items from the test facility interface meeting:

a. A listing of instrumentation for the LH_2 turbopump tests showing types of sensors, quantities, ranges, and sampling rates.

b. After receipt of the SSC basic test facility definition, preparation of sketches showing the orientation of the turbopump in the test facility was initiated. This will be delivered in the July reporting period, along with the required fluid flows and conditions at the interface points.

Cost Account Plans (CAPs) were finalized and put in place during the report period. The required effort is now authorized and proceeding.

To enhance our simultaneous engineering approach (an essential TQM element) key personnel will be colocated within a dedicated ALS office area next month.

<u>WBS 4.1.0</u> - Delivery of data items will henceforth be reported under Section 2.6 "Correspondence".

2.2 SCHEDULE

All tasks are on-schedule at close of this reporting period other than the cost model, which requires NASA input before major effort can commence.

The Master Schedule for the LH_2 Turbopump Program is shown in Figure 4. Milestones are defined in the Milestone Dictionary, Figure 5. The DR delivery schedule is given in Figure 6. Figure 7 shows the percentage completion on the ALS Master Network. All schedules indicate program status as of close of the reporting period.

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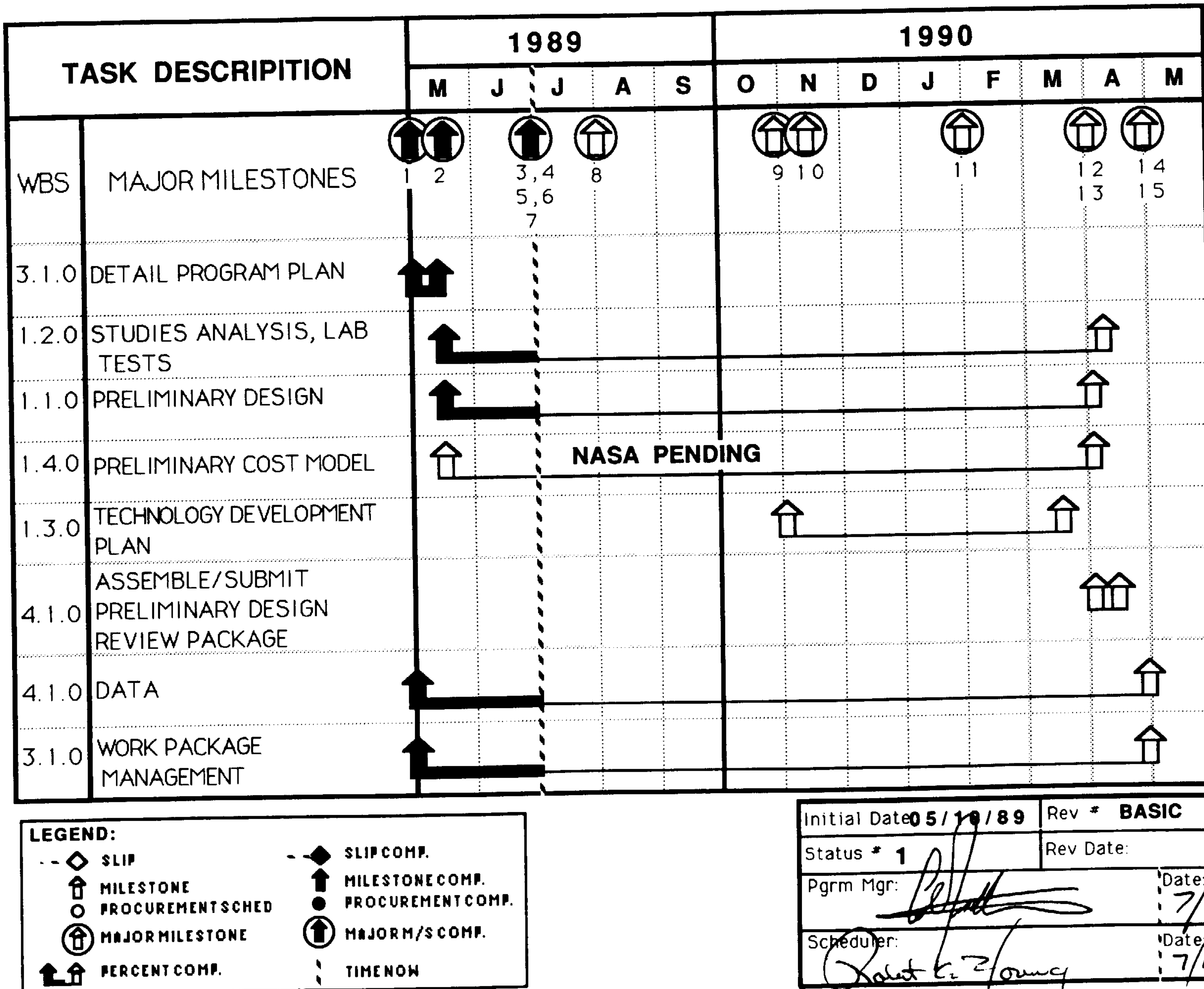
ALS LIQUID HYDROGEN TURBOPUMP MASTER SCHEDULE

CONTRACT No. NAS8-37593



Initial Date 05/10/89	Rev # BASIC
Status # 1	Rev Date:
Pgrm Mgr:	Date: 7/12/89
Scheduler: Robert E. Young	Date: 7/12/89

Figure 4. Master Schedule

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ALS LIQUID HYDROGEN TURBOPUMP MILESTONE DICTIONARY

CONTRACT No. NAS8-37593

MILESTONE NUMBER	DESCRIPITION	REQUIREMENT DATE	STATUS	DATE COMPLETED
1	ATP	01 MAY 1989	Complete	01 MAY 1989
2	SUBMIT REVISE IMPLEMENTATION TECH PROGRAM PLAN DR-15	15 MAY 1989	Complete	15 MAY 1989
3	FACILITIES PLAN DR-04	29 JUN 1989	Complete	23 JUN 1989
4	GFP MANAGEMENT PLAN DR-06	29 JUN 1989	Complete	23 JUN 1989
5	LOGIC NETWORK, KEY MILESTONES DR-16	29 JUN 1989	Complete	28 JUN 1989
6	QUALITY PLAN DR-17	29 JUN 1989	Complete	29 JUN 1989
7	SYSTEM SAFETY PLAN DR-25	29 JUN 1989	Complete	27 JUN 1989
8	1st QUARTERLY REVIEW	01 AUG 1989	Open	
9	PARTS & MATERIAL TRACEABILITY PLAN DR-18	30 OCT 1989	Open	
10	2nd QUARTERLY REVIEW	09 NOV 1989	Open	
11	3rd QUARTERLY REVIEW	01 FEB 1990	Open	
12	SUBMIT DATA/DOCUMENTATION FOR PDR DR-27	12 APR 1990	Open	
13	INTERFACE CONTROL DOCUMENT DR-28	12 APR 1990	Open	
14	CONTRACT END ITEM SPEC DR-26	27 APR 1990	Open	
15	PDR/FINAL REPORT DR-24	27 APR 1990	Open	

Initial Date: 05/25/89	Rev # BASIC
Status #	Rev Date:
Pgrm Mgr:	Date: 7/12/89
Scheduler:	Date: 7/12/89

Figure 5. Milestone Dictionary

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Liquid Hydrogen Turbopump
Schedule Determined by DR
Contract No. NAS8-37593

Initial Date: 05/12/89	Rev. #	Rev. Date	Status #: 1	Date: 07/11/89
Program Manager: [signature]			Date: 7/12/89	
Program Scheduler: [signature]			Date: 7/12/89	

DR Title	DR No.	1989 May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	1990 Jan	Feb	Mar	Apr	May
Mo. Financial Mgmt. Rpt.	01		● 9	●14		○8	○13		○8	○12		○9	○13	
Qtr. Financial Mgmt. Rpt.	02				○15			○15			○15			○15
Mo. Progress Report	03		●16	●21	○18	○15	○20	○17	○15	○19	○16	○16	○20	○18
Facility Plan	04		● 29										30○	(PDR)
Equipment List	05													
Govt. Furnished Property Plan	06		● 29											
Propellant & Pressurant Use	07	End of First Month of Usage												
Propellant & Pressurant Forecast	08						○15						○15	
Pack, Hndl, Transp Recs & Procs	09	As Required												
Material Usage Agreement	10	As Required												
Accident/Incident Report	11	As Required										30○		
Hazard Analysis Report	12													
Contractor Documentation	13	As Required												
Documentary Photo Req.	14	As Required												
Technical Implementation Plan	15	●15												
Logic Network and Key Milestone Chart	16		● 29	Then Update Monthly										
Quality Program Plan	17		● 29											
Material & Process Spec List	18						27○							
Material & Process Spec List - Qtrly.	19				○			○			○			○
Acceptance Plan	20	Present at DDR												
Not Assigned	21													
Manufacturing Plan	22	Present at DDR												
Material Control Plan	23		● 29	(Prelim. MUIL)		(Update)○			(Update)○			(Update)○		
Final Report	24												30○	(PDR)
System Safety Plan	25		● 29											
Contract End Item Specification	26												30○	(PDR)
Pack Requirements & Design Reviews	27												12○	
Interface Control Document	28	As Required												
Drawing List, Form 1, Specs & Microfilm	29	As Released												
Turbopump & Cont Effector Sys. Test Plan	30	14 Days Prior to DDR/14 Days Prior to Delivery												
Acceptance Data Package	31	14 Days Prior to Acceptance Review												
Maintenance Requirements	32	60 Days After Drawing Release												
Test Support Documentation	33	As Required												
Test Result Report	34	30 Days Following Test												
Program Month		1	2	3	4	5	6	7	8	9	10	11	12	13

Figure 6. DR Schedule

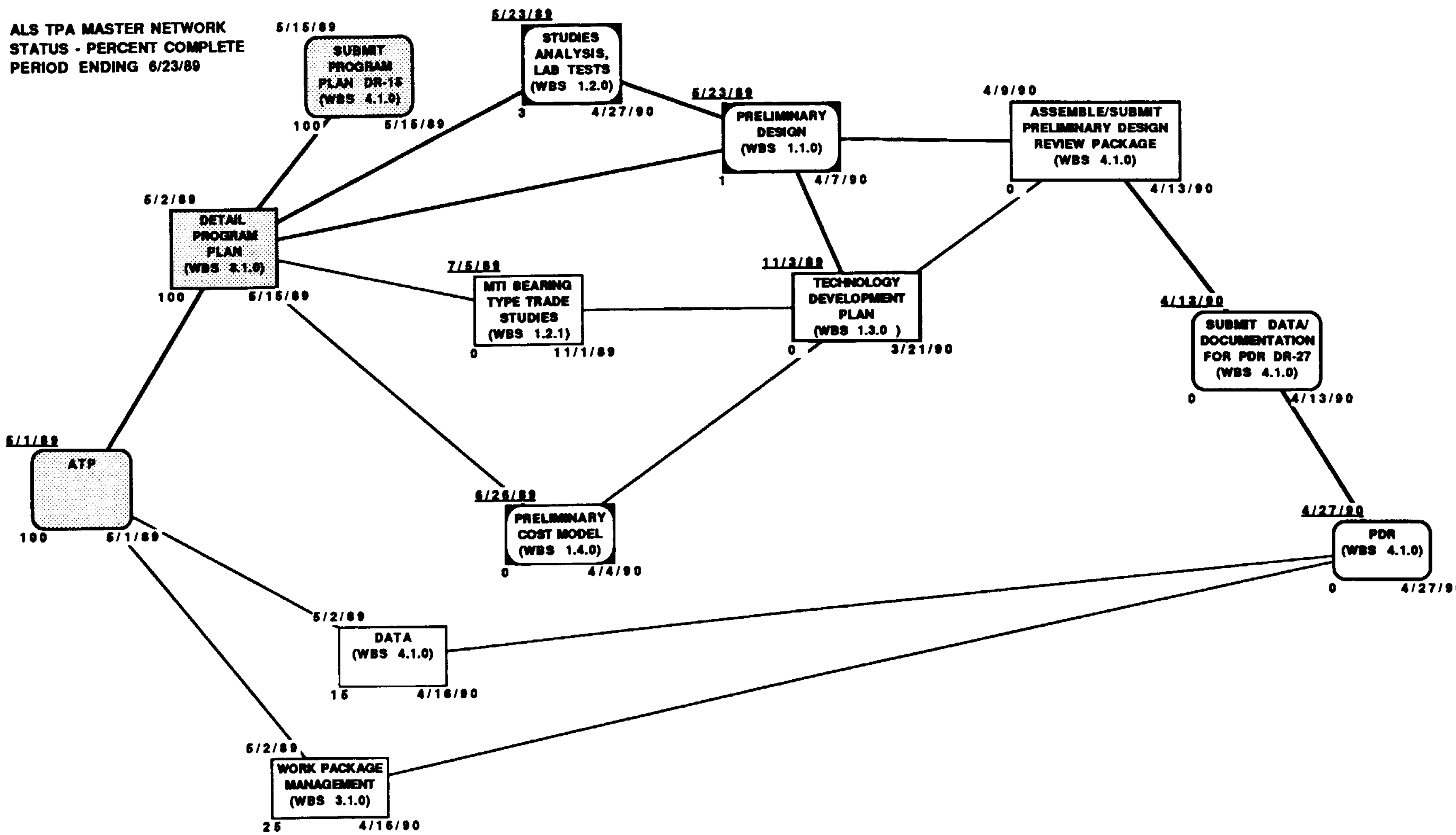

Figure 7. Master Network

2.3 MANPOWER

Figure 8 presents our manpower assessment of the program, showing cumulative manhours expended versus those planned. For this accounting month of June 1989 (20 May program start through 23 June), we were 16% under budget.

2.4 PLANNED WORK FOR NEXT REPORTING PERIOD

2.4.1 Place MTI under subcontract and initiate effort.

2.4.2 Select supplier for cast titanium impellers and place under subcontract.

2.4.3 Initiate procurement process on test bars for materials testing program.

2.4.4 Continue baseline turbopump preliminary design effort.

2.4.5 Continue conceptual design of test cart.

2.4.6 Start low cost trade studies effort using POD design as the reference point.

2.4.7 Submit test instrumentation data for SSC.

2.4.8 Initiate cost model work.

2.5 CORRESPONDENCE

The following lists correspondence and data received from and transmitted to NASA during the reporting period:

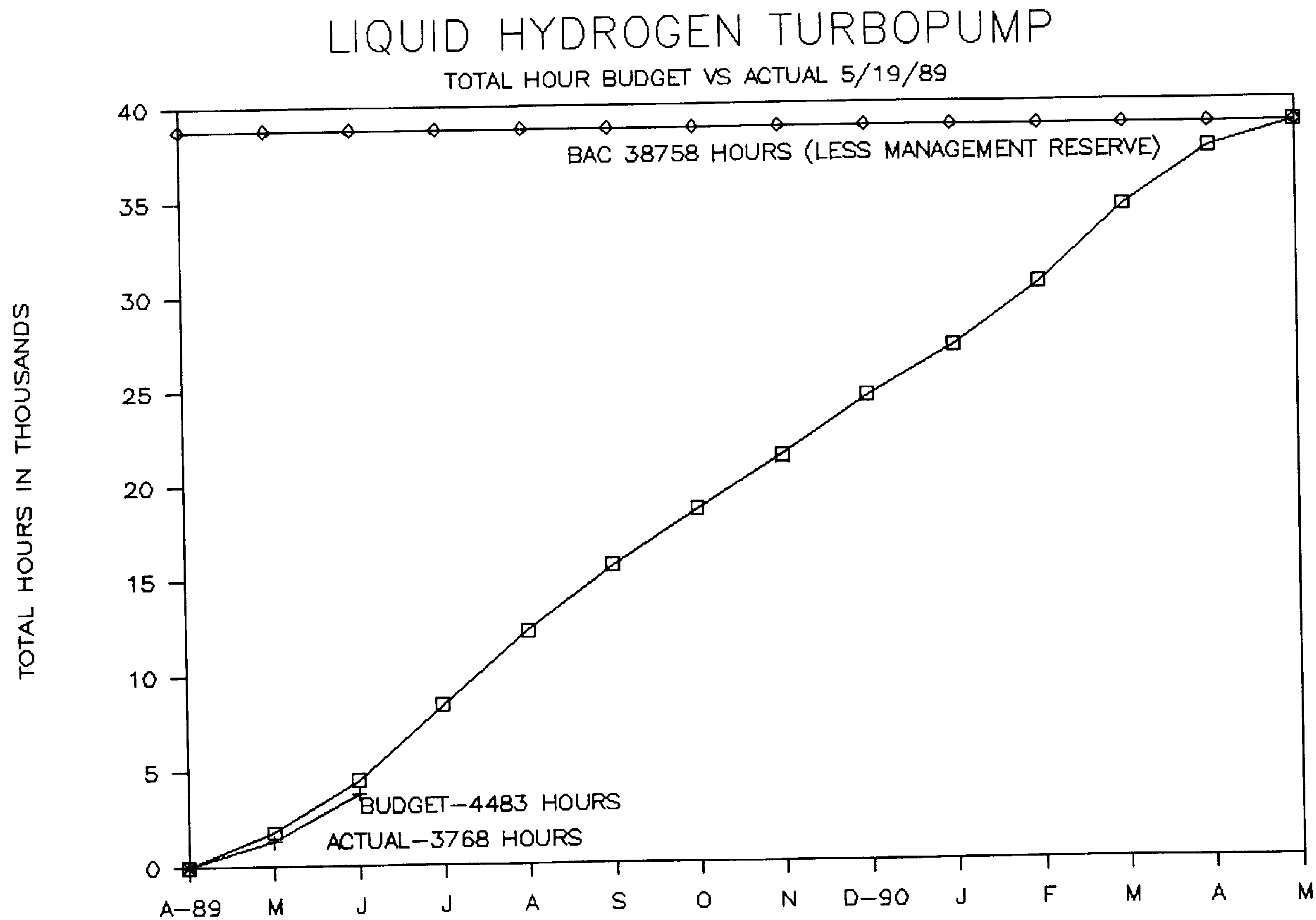

Figure 8. Total Hour Budget vs. Actual

2.5, Correspondence (cont)

Incoming Corres. Date	Subject	Originator
5/22	Contract NAS8-37593, copies for signature	
5/25	NAS 8-37593, Appointment of Contracting Officer's Technical Representative	CC Mitchell/NASA-MSFC
6/5	Contract NAS8-37593	CC Mitchell/NASA-MSFC
6/9	New Technology Reporting Requirement of Contracts NAS8-37593, NAS8-38073, and NAS8-38074	I Akbay/NASA-MSFC
6/16	Contract NAS8-37593, Modification No. 1	CC Mitchell/NASA-MSFC

Outgoing Corres. No.	Date	Subject	Originator
9001:0001	6/1	Contract NAS8-37593, Acknowledgement	CS Montgomery
9001:DM2360	6/9	Contract NAS8-37593, Financial Management Report 533M, DR-01	CS Montgomery
9001:DM2372	6/16	Contract NAS8-37593, Monthly Progress Report, DR-03	CS Montgomery
9001:DM2375	6/23	Contract NAS8-37593, Facilities Plan DR-04, 29 June 1989	CS Montgomery
9001:DM2392	6/23	Contract NAS8-37593, Government Furnished Property (GFP) Management Plan, DR-06	CS Montgomery

3.0 TECHNICAL PROBLEMS AND PROPOSED SOLUTIONS

3.1 Responses from casting suppliers indicate that receipt of production-standard deliverable cast impellers may occur after the planned end date for Phase I. Development castings will be available during Phase I, which will support determination of material properties using test bars extracted from actual castings. The schedule may not, however, support planned spin testing of cast impellers in Phase I.

Aerojet will attempt to improve the schedule in meetings with suppliers during the July report period. One possibility would be to produce the deliverable castings in the supplier's development facility, rather than the production facility as now planned, avoiding the changeover delay.

4.0 SPECIAL NASA CONCERNS

4.1 During the conceptual design effort on the test cart, it became apparent that a cart for each turbopump, cold gas and hot gas, would greatly expedite transportation, handling, and testing of the test articles during Phase II. The present scope calls for fabrication of one test cart only. Aerojet recommends inclusion of a second test cart to improve test operations productivity.

4.2 NASA needs to provide Aerojet with the Contract End Item Specification to facilitate construction of the Cost Model architecture.

Attachment 1

Kickoff Meeting Charts

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ADVANCED LAUNCH SYSTEM
ADVANCED DEVELOPMENT PROGRAM
LIQUID HYDROGEN TURBOPUMP
KICK-OFF MEETING

(Contract No. NAS 8-37593)

NASA—George C. Marshall Space Flight Center

8 June 1989

M4D9/ALS H2 TPA/3

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Kick-Off Meeting Objectives

- Implementation Plan Familiarization
- Identify NASA-Aerojet Links on Program
- Identification of Relevant NASA Resources:
  - Data
  - Tools

M4D9/ALS H2 TPA/3

"When cost is a performance variable in engine design, the challenge is different."

- Col. Jack Wormington, USAF,
ALS Program Director

"To achieve our goals for cost reduction, we've got to find new ways of doing business."

- Jerry Thomson, NASA-MSFC

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Agenda—AM

Program Organization & Overview	C. Faulkner
PHASE I:	
Preliminary Design	N. Shimp
Studies, Analyses, and Lab. Tests	N. Shimp/G. Claffy
Technology Development	G. Claffy
Preliminary Cost Model	C. Faulkner

M4D9/ALS H2 TPA/3

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Agenda—PM

PHASE II:

Detailed Design	N. Shimp
Studies, Analyses and Lab. Tests	N. Shimp
Component Test Article Fabrication	G. Claffy
Test Planning, Support & Analysis	G. Claffy
Detailed Cost Model	C. Faulkner
CONCLUDING REMARKS	C. Faulkner

M4D9/ALS H2 TPA/3

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Program Organization And Overview

- Program Goals
- Basic Approach
- The Aerojet Team
- Coordinated Total Plan

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Program Objectives

- Provide Proven Low Cost Technologies for Successful LH_2 Turbopump:
  - — Lowest Cost With Required Reliability
  - — Acceptable Performance and Weight
  - — <u>NO</u> Compromises With Safety

M4D9/ALS H2 TPA/3

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Technologies Derived From STME/STBE Studies

- Conservative Design Criteria and Margins
- Extensive Use of Castings
- Bolted Assembly/No Assembly Welds
- Standardization Within Turbopump
  - Impeller Castings
  - Rotor Discs
  - Blade Attachments
  - Bearings
- Proven Materials and Fabrication Processes
- Minimum Weld Joints
- Minimize Plating and/or Coatings
- Participative Supplier Base
- Organization/Specification/Procedure Changes
- Advanced Machining
- Commonality Between Turbopumps
  - Blade Attachment/Dampers
  - Rotor Discs
  - Bearing Sets

M4D9/ALS H2 TPA/3

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Reliability Assessments Throughout The Program

- Materials Testing
  - — As Processed
  - — In Environment
  - — Sacrificed Subcomponents
- Early Impeller Development
- Probabilistic Design
- Bearing Development Program
- Proof and Spin Tests During Fab
- Calibration of Analytical Models
- Validation of Internal Environment
- Hot Fire Tests at Full Loads

M4D9/ALS H2 1PA-2

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Cost Is Assessed Throughout The Program

- Quantify Cost Reduction With Trade Studies
- Feasibility Proven Experimentally
  - Fab Experiments
  - Design Iterations
  - Process Development/Supplier Interaction
  - Specification Development
  - Parts Manufactured
  - Inspection Techniques Evaluation
  - Testing at Full Loads
- Cost Model Development
  - 1st Unit Cost Validation

M4D9/ALS H2 TPA/2

Performance Is Assessed Throughout The Program

- Conventional Analysis
- Advanced Analysis
- Tolerance Analysis
- Cold Gas, Heavily Instrumented Turbopump
  - — Calibration of Analytical Model
- Full-Scale Testing (Hot Gas)
  - — Unit-to-Unit Variations

M4D9/ALS H2 TPA/4

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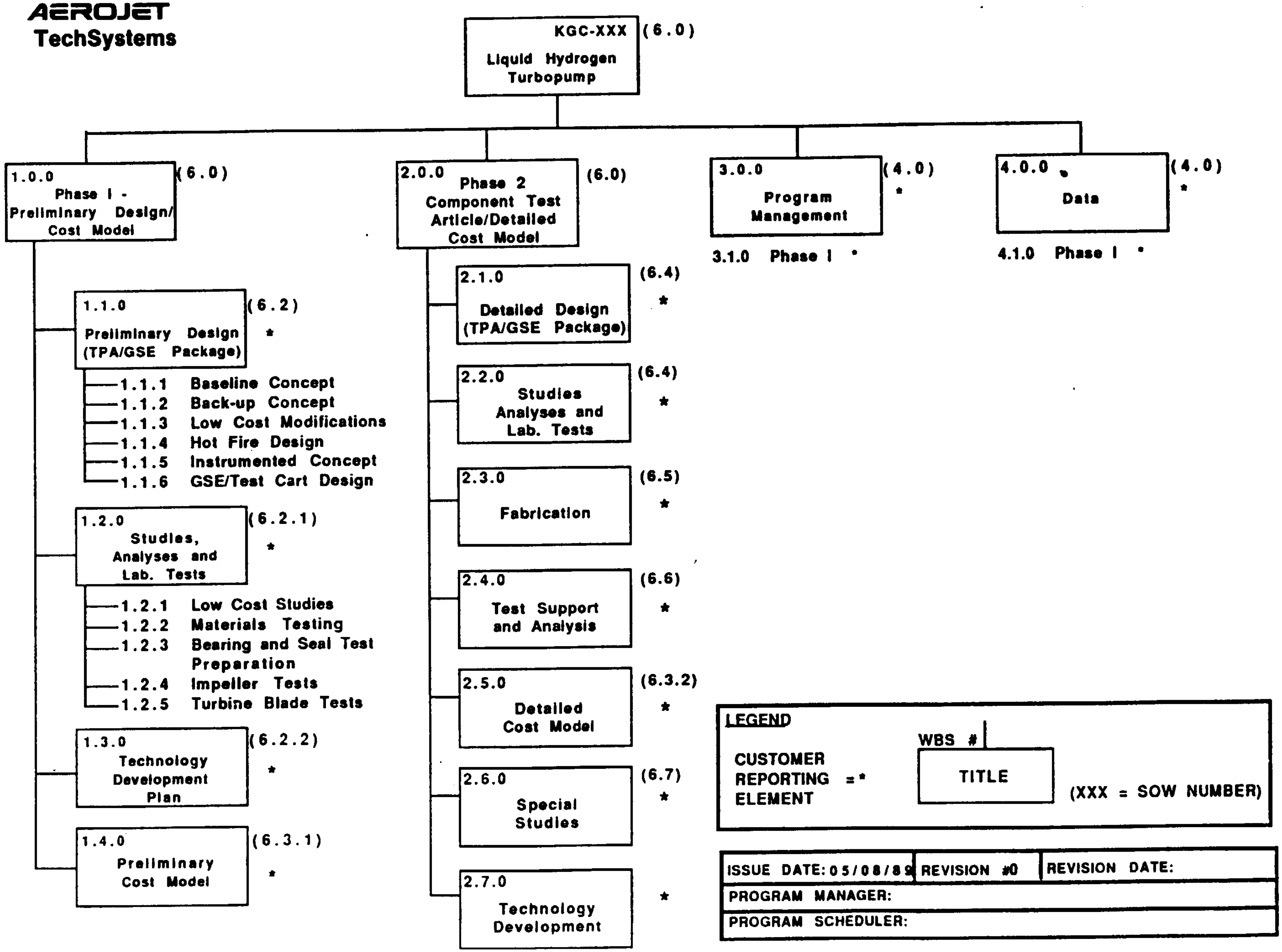
Program Is Structured Around WBS



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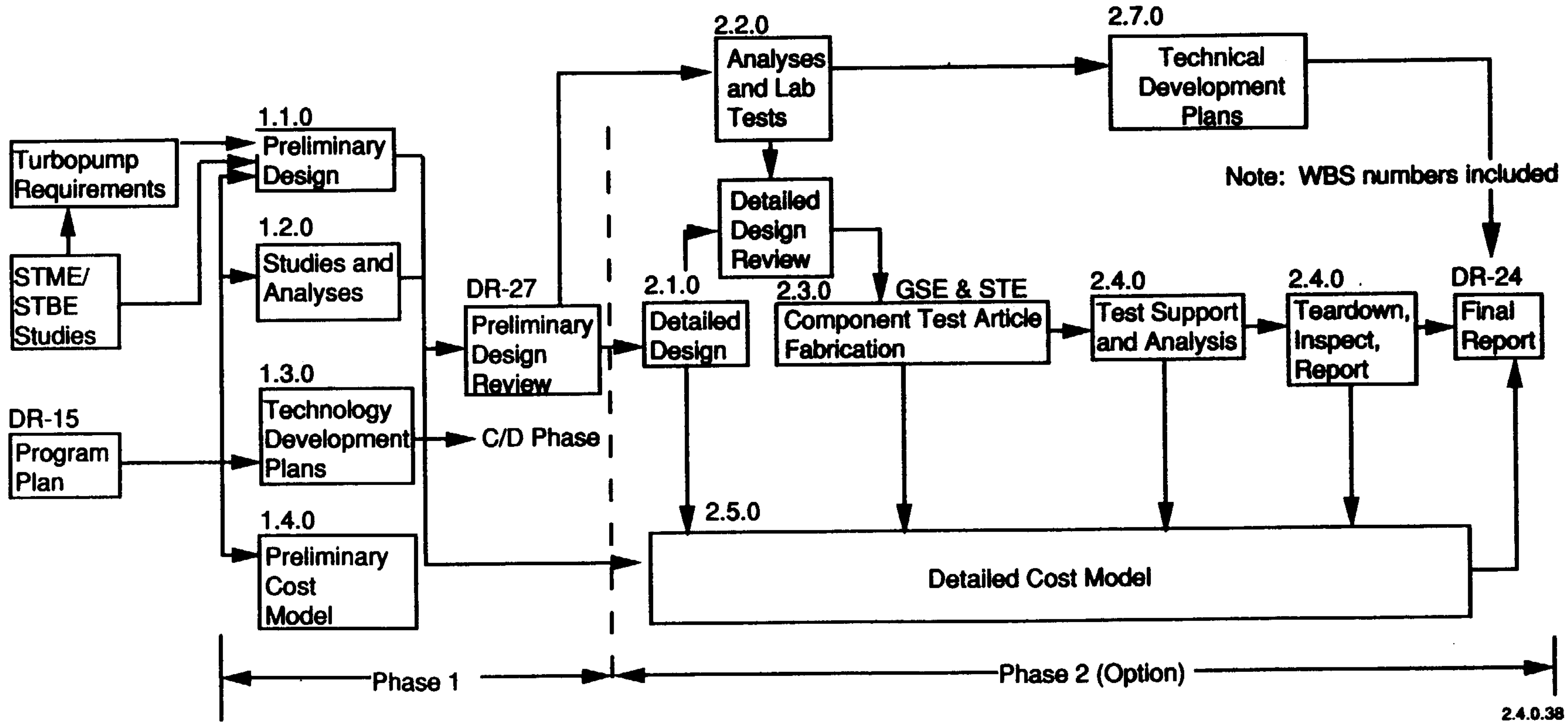
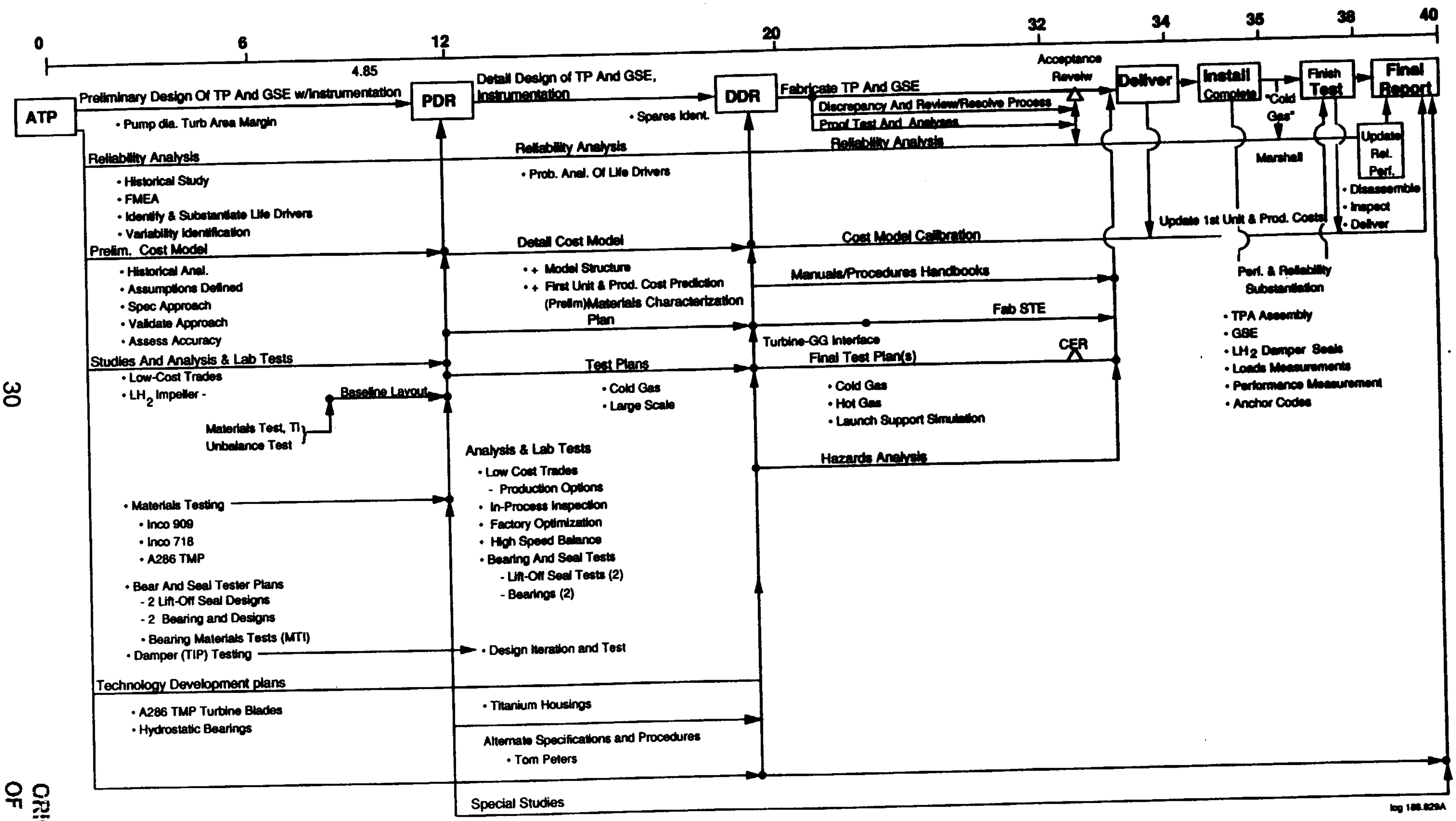
Top Level Program Logic



Coordinated Total Plan



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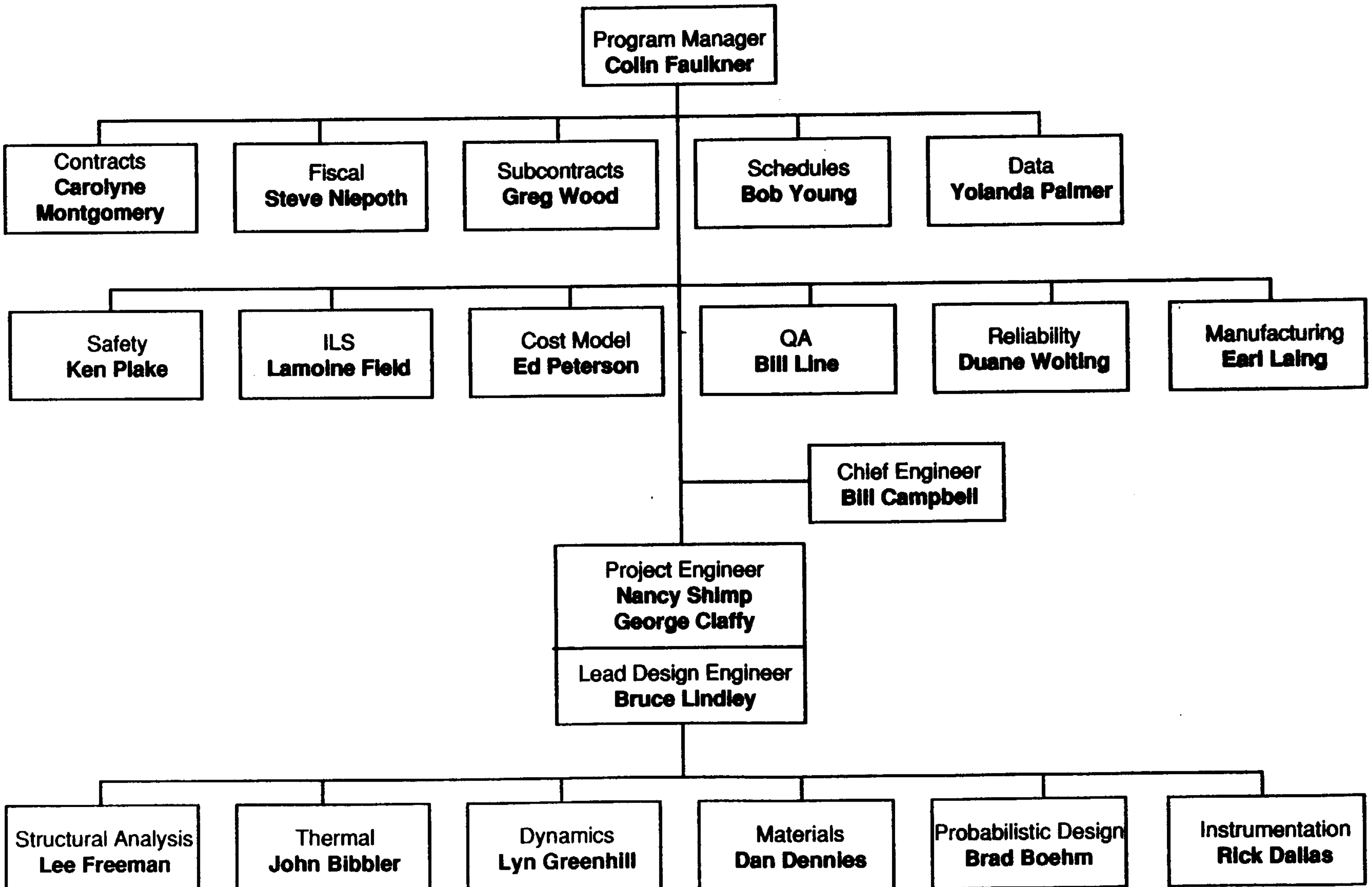
Program Organization



2.4.0.39

Aerojet's Industrial Team

- Aerojet TechSystems — Contractor
- Mechanical Technology Inc. — Balancing, Advanced Mfg., Bearings and Seals Support
- Ingersoll Engineers — Production Planning
- Trimet — Materials Support
- Tom Peters Group — Organization & Procedures
- Participative Supplier Base — Castings, Forgings, etc.

M4D9/ALS H2 TPA/3

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Subcontractors Have Well-Defined Tasks

- INGERSOLL ENGINEERS
  - — Cost Substantiation
  - — Production Manufacturing Strategy
  - — Facility and Equipment Optimization
  - — Manufacturing Organization Streamlining
  - — Aerospace/Defense and Commercial Cost Data
  - — Quality Function Integration

- MECHANICAL TECHNOLOGY INC. (MTI)
  - — Bearing and Seal Technologies
  - — Instrumentation and Test Planning
  - — Advanced Manufacturing Technology
    - In-Process Machine Control
    - On-Machine Inspection
    - Automated Balancing

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Emphasis On TQM

- Simultaneous Engineering
- Probabilistic Design
- Colocated Core Team
- Participative Subcontractors and Suppliers
- Organization-Wide Education and "Ideas Gathering"

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Key Program Deliverables

- Test Articles Package:
  - Turbopumps Incorporating Results of Studies, Trades, Analyses, and Experiments
  - Test Cart With "Clean" Test Facility Interfacing for Improved Test Productivity
  - Ground Support Equipment, STE
- Results and Analysis of Tests at NASA-SSC
- Materials and Processes Data
- Material Characterization Plan
- Technology Development Plans
- Cost Model Anchored With Program Data:
  - Projected Recurring Production and Operations Costs
  - Recommended Specification and Procedure Savings

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Our Program Includes Two Test Articles

- Unit No. 1 - Cold Gas Tests (Heavily Instrumented)
  - Understanding the Internal Turbopump Environment
  - Major Element of Integrated Analysis/Test Effort
- Unit No. 2 - Hot Gas Tests
  - Simulate Actual Engine Operating Environment

Fuel Turbopump Commonality Offers <u>Option</u> to Operate One Test Article in STME (LH_2) and STBE (LCH_4) Modes

M4D9/ALS H2 TPA/3

The Program

Phase I
(12 Months)

- Preliminary Design
- Analyses and Trades
- Lab. Tests
- Preliminary Cost Model

Phase II - Option
(28 Months)

- Detail Design
- Analyses & Lab. Tests
- Fabricate Two Turbopumps
  - — Cold Gas/Instrumented
  - — Hot Fire/Flight Type
- Fabricate Test Cart and GS
- Test Support to SSC
- Detailed Cost Model

Preliminary Design
(WBS 1.1.0)

Nancy Shimp

Objective: To Develop a Master Dimensional Layout Based on the Results of the Analyses and Lab Tests

M4D9/ALS H2 TPA/3

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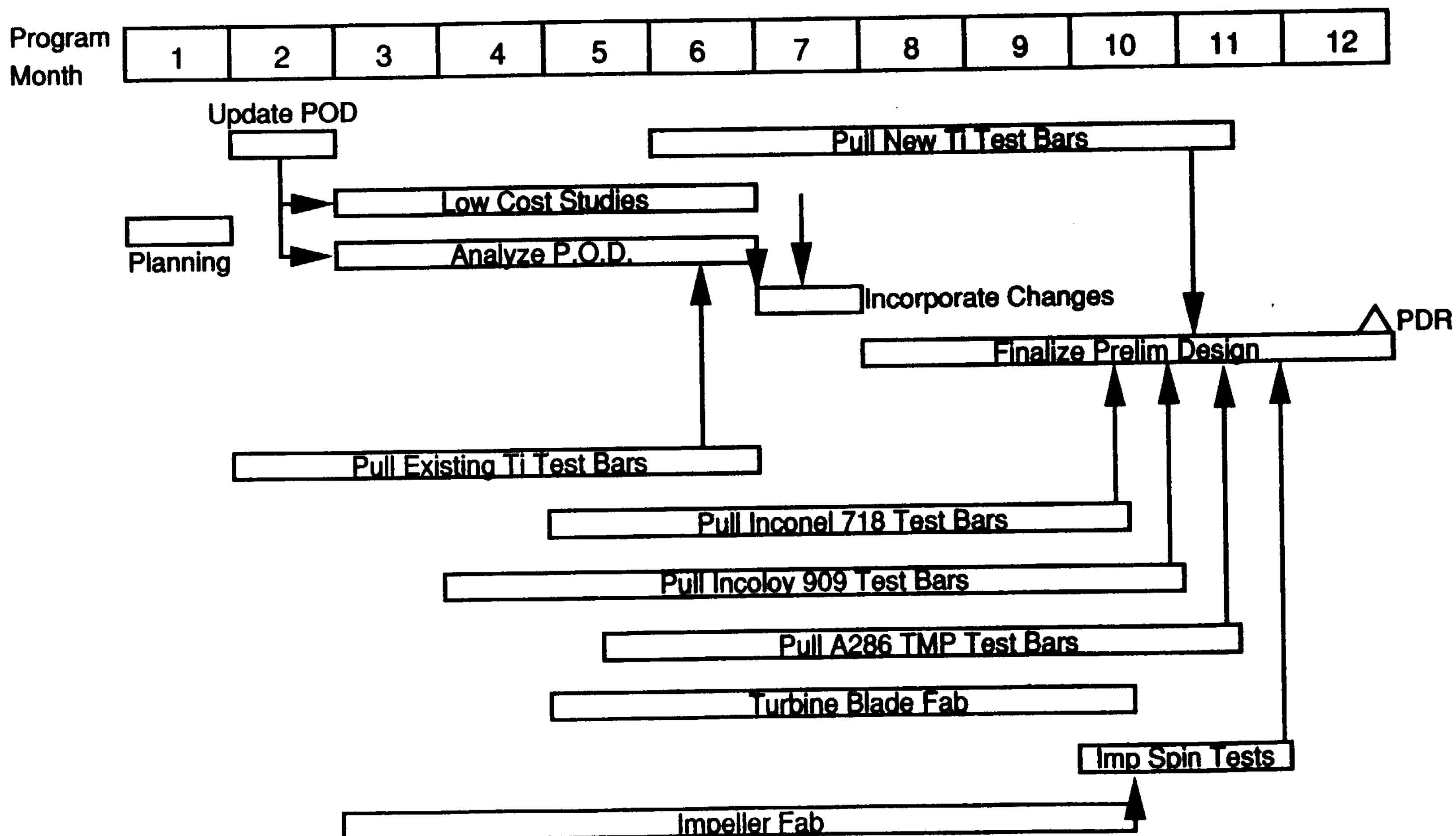
Phase I Program Focuses On Feasibility Of Concept

- Experiments
  - Materials Characterization
  - Impeller Fab
  - Turbine Blade Fab
  - Bearing and Seals
- Trades
  - Design Options
  - Maintainability
  - Commonality
- Preliminary Design
  - Create Master Dimensional Layout
  - Analyses to Determine Feasibility
  - Initial Load Assessment
- Cost Model Development
  - Preliminary Data Base

M4D9/ALS H2 TPA/2

Program Achieves Phase I Objectives



2.4.0.41

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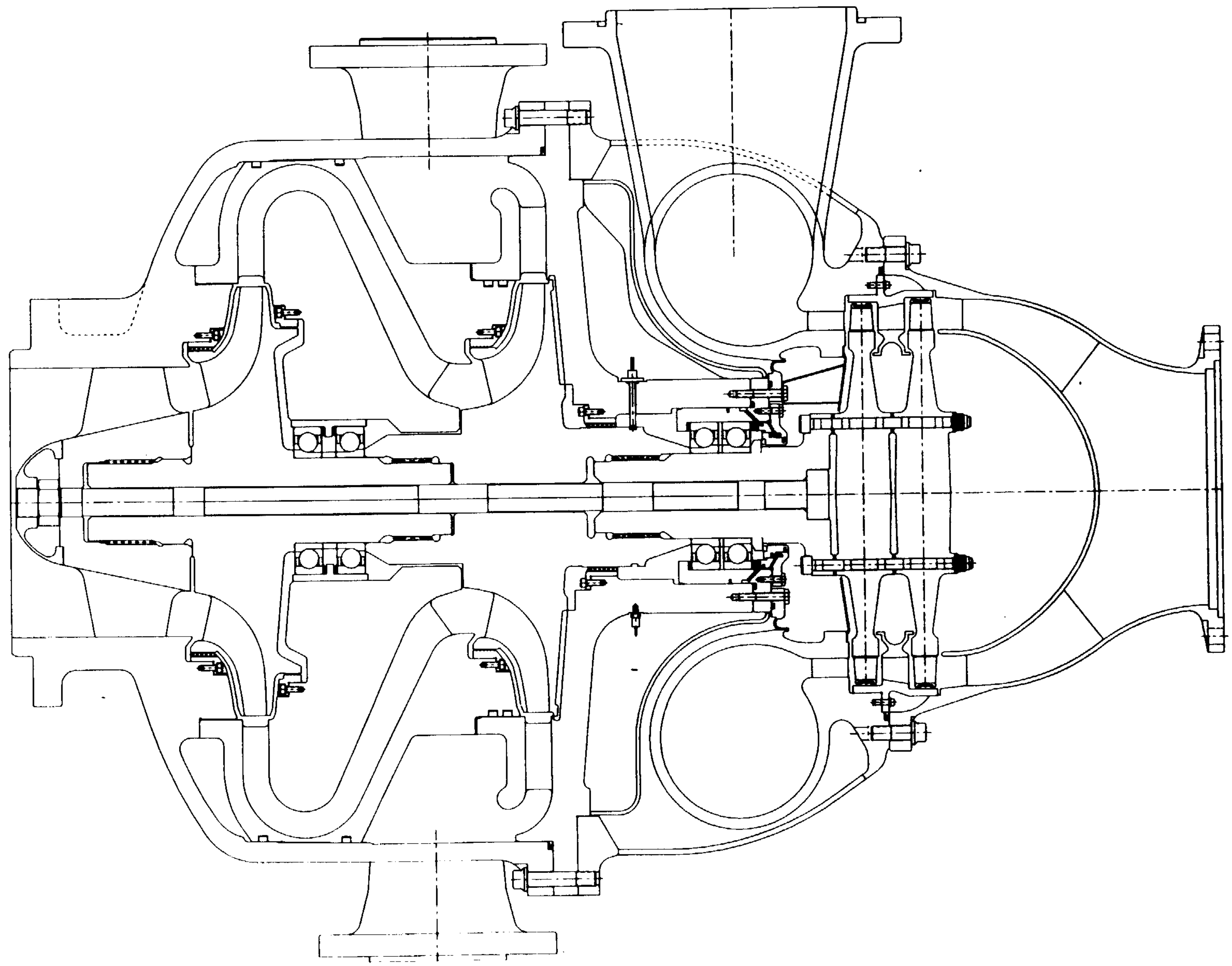
POD Design Includes Proven Low Cost Features



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Update POD Design To Include Latest Results Of Phase A Studies

- Update POD Design
  - Include Results of Phase A Studies
  - Relax Commonality Requirements With LOX Pump
    - Pump Collector
      - Single Discharge
      - Volute Type
    - Turbine Manifold Redesign
      - Baseline-Integral Cast Nozzles
      - Thermal Growth Allowances
      - Castability
      - Torus Area Reduction
    - Turbine Disc Optimization
      - Blade Chord Reduction
    - Bearing Load Path

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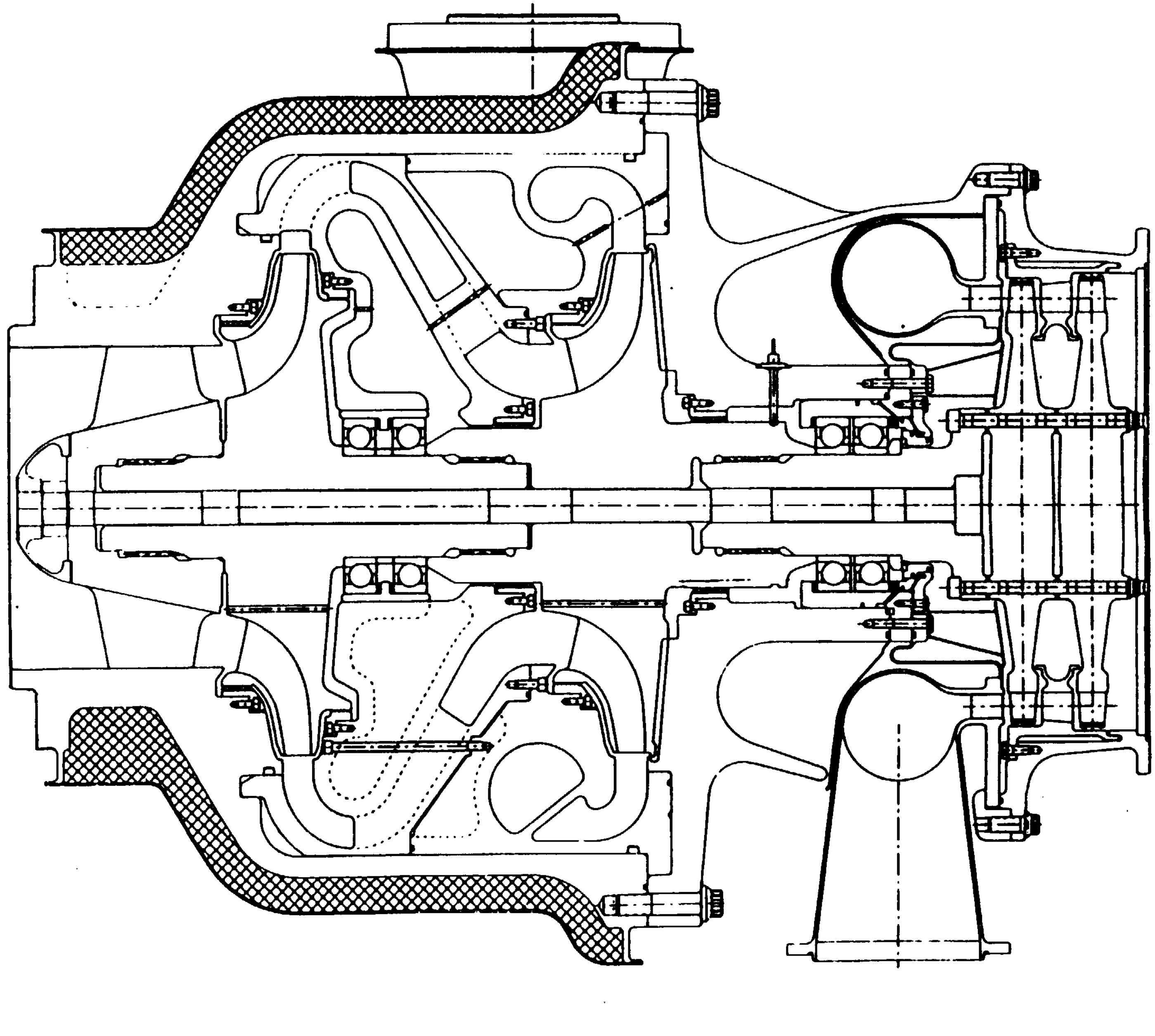
Baseline Design Will Include Developments of Phase A Studies



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Reliability And Cost Trades Begin

- Historical Reliability Analyses
- Reliability Allocations
- Develop a Baseline Start Transient
- Finalize the Design Trades List
- Incorporate Appropriate Performance Margins

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Update POD Design Serves As Anchor For Low Cost Studies

- Updated POD Will Be Used to:
  - Casting Development Experiments
  - FMEA/CIL
  - LEMD
  - Perform Preliminary Analyses
    - Structural
    - Thermal
    - Dynamics
    - Bearing Life
  - Initial Piece Parts Cost
  - Instrumentation
  - Bearing and Lift-Off Seal Design
  - Low Cost Studies
    - Design Options
    - Maintainability
    - Commonality
  - GSE/Test Cart Concept

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A LEMD Document Will Provide A Basis For Analysis

LEMD → Loads, Environmental, Materials Document

- Contains Data Required to Support Design Requirements, Including:
  - Loads on Pump Components
  - Vibratory and Acoustic Environment
  - Uniform Set of Material Properties

- Data for Document Initially Compiled From Several Sources
  - Interface Specifications
  - Pump Design Requirements
  - Previous ATC Experience (Titan)
  - Similar Prior Analyses

- Final Document Intended to Be Revised as New Data Becomes Available
  - Revised Analyses
  - Early Test Data (Hot Fire, Cold Gas)

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While The Low Cost Trades Are Performed, Maturity Of The POD Design Improves With Analyses

Baseline Analyses

- Pump Hydraulics
- Turbine Aerodynamics
- Dynamics
- Power Transmission
- Thermal
- Structural
- Reliability

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Proven Pump Analysis Codes Will Be Used

ANALYSIC CODE NO.	ANALYSIS CODE DESCRIPTION	ANALYSIS CODE OUTPUT	ANALYSIS CODE VERIFICATION BASIS
1	1D Meanline	1D Meanline Pressures, Velocities and Pressure Losses	ATC Experience Base
2	2D Inviscid -"KATSANIS" "McFARLAND"	Inviscid 2D Pressures, Velocities and Flow Angles	ATC Experience Base Industry/NASA Standard
3	2D Viscous (Navier Strokes) - "AEROVISC", "PHOENICS", "FIDAP"	Viscous 2D Pressures, Velocities, Flow Angles and Pressure Losses	IR&D Validation Plan for "AEROVISC" Existing Empirical Data Base for "PHOENICS" and "FIDAP"
4	Quasi 3D Inviscid - "KATSANIS"/ "MERIDL"	Inviscid 3D Pressures, Velocities and Flow Angles	ATC Experience Base Industry/NASA Standard
5	3D Viscous (Navier Strokes) - "AEROVISC", "PHOENICS", "FIDAP"	Viscous 3D Pressures, Velocities, Flow Angles and Pressure Losses	IR&D Validation Plan for "AEROVISC" Existing Empirical Data Base for "PHOENICS" and "FIDAP"
6	Design Codes — "IMP1INC", "STA1D", "IMP3D", "VOLUTE", "CROSS"	Geometry - 2D Rotor Blade, 2D Stator Vane, 3D Rotor or Stator, and 3D Volute Shapes	ATC Experience Base
7	CDF Analysis, Pre and Post Processor Codes - "PATRAN"/ "TRANSLATE", "OTHER ROUTINES"	Advanced Mesh Generation and Color Graphics to Aid in Rapid CFD Design and Analysis	ATC Experience Base

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Pump Design Elements Are Integrated Into A Concerted Analysis Effort

Element	Input Source	Analysis Codes		Test Verification
		Preliminary Design	Detail Design	
1. Pump Inlet Flange	SOW, ICD, LEMD	EDC, 1	1	CGT, HGT
2. Inducer	CDC, LEMD, PE	EDC, 6	5, 7	CGT, HGT
3. Impeller	CDC, LEMD, PE	EDC, 2, 4, 6	5, 7, 8	CGT, HGT
4. Vaneless Space	LEMD, PE	EDC, 1		CGT, HGT
5. Diffuser/Crossover	LEMD, PE	EDC, 2, 4, 6	3, 5, 7, 8	CGT, HGT
6. Discharge Collector	LEMD, PE	EDC, 6	5, 7	CGT, HGT
7. Discharge Ducts	SOW, ICD, LEMD, PE	EDC, 1	5, 7	CGT, HGT

SOW = Statement of Work
ICD = Interface Control Document
LEMD = Loads, Environment, and Material Documentation
PE = Previous Element Analyzed
CDC = Conservative Design Criteria
EDC = Empirical Design Correlation

CGT = Cold Gas Tests at Stennis Space Center
HGT = Hot Gas Tests at Stennis Space Center

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Proven Turbine Analysis Codes Will Be Used

ANALYSIC CODE NO.	ANALYSIS CODE DESCRIPTION	ANALYSIS CODE OUTPUT	ANALYSIS CODE VERIFICATION BASIS
1	1D Meanline	1D Meanline Pressures, Temperature, Velocities and Pressure Losses	ATC Experience Base
2	2D Inviscid -"KATSANIS"/ "McFARLAND"	Inviscid 2D Pressures, Temperature,Velocities and Flow Angles	ATC Experience Base Industry/NASA Standard
3	2D Viscous (Navier Strokes) - "AEROVISC", "PHOENICS", "FIDAP"	Viscous 2D Pressures, Temperature, Velocities, Flow Angles and Pressure Losses	IR&D Validation Plan for "AEROVISC" Existing Empirical Data Base for "PHOENICS" and "FIDAP"
4	Quasi 3D Inviscid - "KATSANIS"/ "MERIDL", "WENNERSTROM"	Inviscid 3D Pressures, Temperature Velocities and Flow Angles	ATC Experience Base Industry/NASA Standard
5	3D Viscous (Navier Strokes) - "AEROVISC", "PHOENICS", "FIDAP"	Viscous 3D Pressures, Velocities, Flow Angles and Pressure Losses	IR&D Validation Plan for "AEROVISC" Existing Empirical Data Base for "PHOENICS" and "FIDAP"
6	Design Codes - "MULTISTG", "OFFTURB"	Geometry - Basic Sizing, Off-Design Performance	ATC Experience Base
7	CDF Analysis, Pre and Post Processor Codes - "PATRAN"/ "TRANSLATE", "OTHER ROUTINES"	Advanced Mesh Generation and Color Graphics to Aid in Rapid CFD Design and Analysis	ATC Experience Base

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Turbine Design Elements Are Integrated Into A Concerted Analysis Effort

Element	Input Source	Analysis Codes		Test Verification
		Preliminary Design	Detail Design	
1. Turbine Inlet Flange	SOW, ICD, LEMD	EDC, 1		CGT, HGT
2. Turbine Inlet Manifold	SOW, ICD, LEMD, PE	EDC, 1,	5, 7	CGT, HGT
3. Nozzle Vanes (1st and 2nd Stage)	LEMD, PE	EDC, 2, 6	3, 5, 7, 8	CGT, HGT
4. Rotor Blade (1st and 2nd Stage)	LEMD, PE	EDC, 2, 6	3, 5, 7, 8	CGT, HGT
5. Turbine Exhaust w/ Guide Vanes	SOW, ICD, LEMD, PE	EDC, 1, 2	5, 7	CGT, HGT

SOW = Statement of Work
ICD = Interface Control Document
LEMD = Loads, Environment, and Material Documentation
PE = Previous Element Analyzed
EDC = Empirical Design Correlation

CGT = Cold Gas Tests at Stennis Space Center
HGT = Hot Gas Tests at Stennis Space Center

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Proven Dynamic Analysis Codes Will Be Used

ANALYSIC CODE NO.	ANALYSIS CODE DESCRIPTION	ANALYSIS CODE OUTPUT	ANALYSIS CODE VERIFICATION BASIS
1	"ANSYS" Finite Element Code	Matrix and Modal Models for Housing, Shaft, Bearing Supports for Use in RODYNE	Commercial Code Industry/NASA Standard
2	"RODYNE" Dynamic Simulation Code	Campbell Diagrams, Root Loci to Show Critical Speed Margin and Stability	ATC Experience Base SSME HPFTP Benchmark with NASA MSFC
3	"ANSYS" Finite Element Code	Detailed Stress Response to Dynamic Loading from Hub Motion and Fluid Pressure	Commercial Code Industry/NASA Standard
4	"RODYNE" Dynamic Simulation Code	Response of Vane/ Hub or Bladed Disc/Rotor/Housing to Imbalance, Hydraulic/Aerodynamic Forces, Rubbing, Transient Operation	ATC Experience Base SSME HPFTP Benchmark with NASA MSFC

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Dynamic Analysis Elements Are Integrated Into A Concerted Analysis Effort

Element	Input Source	Analysis Codes		Test Verification
		Preliminary Design	Detail Design	
1. Rotating Assembly Critical Resonances & Mode Shapes, Lateral	CDC, LEMD	1, 2	1, 2	CGT, HGT
2. Rotating Assembly Critical Resonances & Mode Shapes, Torsional	CDC, LEMD	1, 2	1, 2	CGT, HGT
3. Impeller Blade and Shroud	LEMD, PD	3	1, 3, 4	CGT, HGT
4. Diffuser/Crossover	LEMD, TD	3	3	CGT, HGT
5. Pump Volute	LEMD, TD	3	3	CGT, HGT
6. Nozzle Vanes (1st and 2nd Stage)	LEMD, TD	3	3	CGT, HGT
7. Rotor Disc (1st and 2nd Stage)	LEMD, TD	3	1, 3, 4	LT, CGT, HGT
8. Rotor Blades (1st and 2nd Stage)	LEMD, TD	3	1, 3, 4	LT, CGT, HGT

CDC = Conservative Design Criteria
LEMD = Loads, Environment, and Material Documentation
PD = Pump Design
TD = Turbine Design

CGT = Cold Gas Tests at Stennis Space Center
HGT = Hot Gas Tests at Stennis Space Center
LT = Laboratory Tests

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Proven Power Transmission Codes Will Be Used

ANALYSIC CODE NO.	ANALYSIS CODE DESCRIPTION	ANALYSIS CODE OUTPUT	ANALYSIS CODE VERIFICATION BASIS
1	ATC Code	Flowrates, Pressure Drops, Velocities	ATC Experience Base
2	ATC Code	Axial Thrust Load on Bearings and Balancer	ATC Experience Base
3	1D Bearing Cooling Flow	1D Pressures Mass Flows and Temperature	ATC Experience Base
4	2D Viscous (Navier Strokes) - "AEROVISC", "PHOENICS", "FIDAP"	Viscous 2D Pressures, Velocities, and Mass Flows	IR&D Validation Plan for "AEROVISC" Existing Empirical Data Base for "PHOENICS" and "FIDAP"
5	3D Viscous (Navier Strokes) - "AEROVISC", "PHOENICS", "FIDAP"	Viscous 3D Pressures, Velocities, and Mass Flows	IR&D Validation Plan for "AEROVISC" Existing Empirical Data Base for "PHOENICS" and "FIDAP"
6	CFD Analysis, Pre and Post Processor Codes - "PATRAN"/ "TRANSLATE", "OTHER ROUTINES"	Advanced Mesh Generation and Color Graphics to Aid in Rapid CFD Design and Analysis	ATC Experience Base
7	A. B. Jones	Life, Capacity, Stiffness, Cooling Pressure/Flow Characteristics	ATC Experience Base
8	Shabbreth	Bearing Life and Wear Rates	NASA/SSME
9	"Groove" Damper Seal and Grooved Seal Design	Leakage and Rotordynamic Coefficients for Turbulent Annular Seals	Published Technical Literature, Test Data

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Power Transmission Elements Are Integrated Into A Concerted Analysis Effort

Element	Input Source	Analysis Codes		Test Verification
		Preliminary Design	Detail Design	
1. Axial Thrust Loads	LEMD, TPD	1, 2	1, 2, 4, 6	CGT, HGT
2. Balance Piston Loads and Performance	LEMD, TPD, PA	2	2, 4, 6	CGT, HGT
3. Radial Loads	LEMD, TPD, PA	4, 6	5, 6	CGT, HGT
4. Pump End Bearing Design	LEMD, CDC, PA	3, 7, 8	7, 8	LT, CGT, HGT
5. Turbine End Bearing Design	LEMD, CDC, PA	3, 7, 8	7, 8	LT, CGT, HGT
6. Damper Seal Design	LEMD, CDC, PA, MTI	9	4, 5	LT, CGT, HGT
7. Labrynth/Damper Seal Design	LEMD, CDC, PA	3	4, 5, 6	CGT, HGT

LEMD = Loads, Environment, and Material Documentation
TPD = Tubopump Design Definition(Preliminary or Detail)
PA = Previous Analyses (Pump/Turbine Performance, Stress, Thermal, Dynamics)
CDC = Conservative Design Criteria
MTI = Mechanical Technology, Incorporated

CGT = Cold Gas Tests at Stennis Space Center
HGT = Hot Gas Tests at Stennis Space Center
LT = Laboratory Tests

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Proven Thermal Analysis Codes Will Be Used

ANALYSIC CODE NO.	ANALYSIS CODE DESCRIPTION	ANALYSIS CODE OUTPUT	ANALYSIS CODE VERIFICATION BASIS
1	"SINDA"	Detailed 2D/3D Temperature Distribution	Industry/NASA Standaard
2	"ONE - D - COND"	1D Transient Temperature Distribution	ATC Experience Base/ATC In-House Code
3	"PATRAN"	Model Geometry and Input for "P/THERMAL"	Industry/NASA Standard
4	"P/THERMAL"	2D/3D Temperature Distribution and Stress Analysis Compatible Results	ATC Experience Base Titan Engine Margin Study

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Thermal Analysis Elements Are Integrated Into A Concerted Analysis Effort

Element	Input Source	Analysis Codes		Test Verification
		Preliminary Design	Detail Design	
1. Axisymetric, Transient and Steady State Temperature Profiles	LEMD, TPD	1, 2	2	CGT, HGT
2. Turbine Inlet Manifold Transient and Steady State Temperature Profiles	LEMD, TPD	2	3, 4	HGT
3. Nozzle Vanes (1st and 2nd Stage)	LEMD, TD	2	3, 4	HGT
4. Rotor Disc (1st and 2nd Stage)	LEMD, TD	2	3, 4	HGT
5. Turbine Blades (1st and 2nd Stage)	LEMD, TD	3, 4	3, 4	HGT
6. Exhaust Housing w/ Guide Vanes	LEMD, TD	2	3, 4	HGT

LEMD = Loads, Environment, and Material Documentation
TPD = Tubopump Design Definition(Preliminary or Detail)
TD = Turbine Design

CGT = Cold Gas Tests at Stennis Space Center
HGT = Hot Gas Tests at Stennis Space Center

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Proven Stress Analysis Codes Will Be Used

ANALYSIC CODE NO.	ANALYSIS CODE DESCRIPTION	ANALYSIS CODE OUTPUT	ANALYSIS CODE VERIFICATION BASIS
1	Emperical Correlations	Preliminary Stress Levels	ATC Experience
2	2D Finite Element Models - "ANSYS", "PATRAN"	2D Matrix and Modal Models - Stress Levels	Commercial Code Industry/NASA Standard
3	3D Finite Element Models - "ANSYS", PATRAN	3D Matrix and Modal Models - Stress Levels	Commercial Code Industry/NASA Standard
4	"FLAGRO"	Fatigue Life of Cyclically Loaded Structures with Initial Cracklike Defects	NASA

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Stress Analysis Elements Are Integrated Into A Concerted Analysis Effort

Element	Input Source	Analysis Codes: Preliminary Design	Analysis Codes: Detail Design	Test Verification
1. Inducer	LEMD, PD	1	2, 3, 4	FT, CGT
2. Impeller	LEMD, PD	1, 2, 3,	2, 3, 4	FT, CGT
3. Diffuser/Crossover	LEMD, PD	1, 2	2, 3, 4	FT, CGT
4. Pump Housing	LEMD, PD	1, 2	2, 3, 4	FT, CGT
5. Bearing Housing	LEMD, PTD	1	2	HGT
6. Turbine Inlet Manifold	LEMD, TD	2	2, 3	FT, HGT
7. Turbine Nozzle/Stator	LEMD, TD	2, 4	3, 4	CGT, HGT
8. Turbine Disc	LEMD, TD	2, 4	2, 4	CGT, HGT
9. Turbine Blades	LEMD, TD	2	3, 4	LT, CGT, HGT
10. Turbine Exhaust Housing	LEMD, TD	1	2, 4	FT, HGT
11. Shaft	LEMD, PTD	1, 2	2, 4	CGT, HGT
12. Flange/Fasteners	LEMD	1	1, 2, 3, 4	FT, CGT, HGT
13. Turbopump Mount	LEMD	1	1, 2, 3	HGT

LEMD = Loads, Environment, and Material Documentation
PD = Pump Design
PTD = Power Transmission Design
TD = Turbine Design

CGT = Cold Gas Tests at Stennis Space Center
HGT = Hot Gas Tests at Stennis Space Center
FT = Fabrication Tests (Proof, Burst, Spin)
LT = Laboratory Tests

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MTI Provides Analysis Support For Bearings And Seals

- Bearing Design - Cage Stability
  - CREB or RAPIDRED Computer Codes
- Lift-Off Seals
  - GFACE/SPIRALP Computer Codes
- Damper Seals
  - DSEAL Computer Code
  - Radial Loads
- Bearing Instrumentation
- Bearing Type Trade Study
  - Rolling Element
  - Hybrids
  - Hydrostatic

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MTI Will Conduct Tests To Evaluate Candidate Bearing Materials

- Bearing Materials Tests
  - Material Candidate Selection
  - Rolling Contact Performance Tests
  - Cryogenic Sliding Wear Tests
  - Cryogenic Rolling Wear Tests
  - Stress Corrosion Cracking Tests

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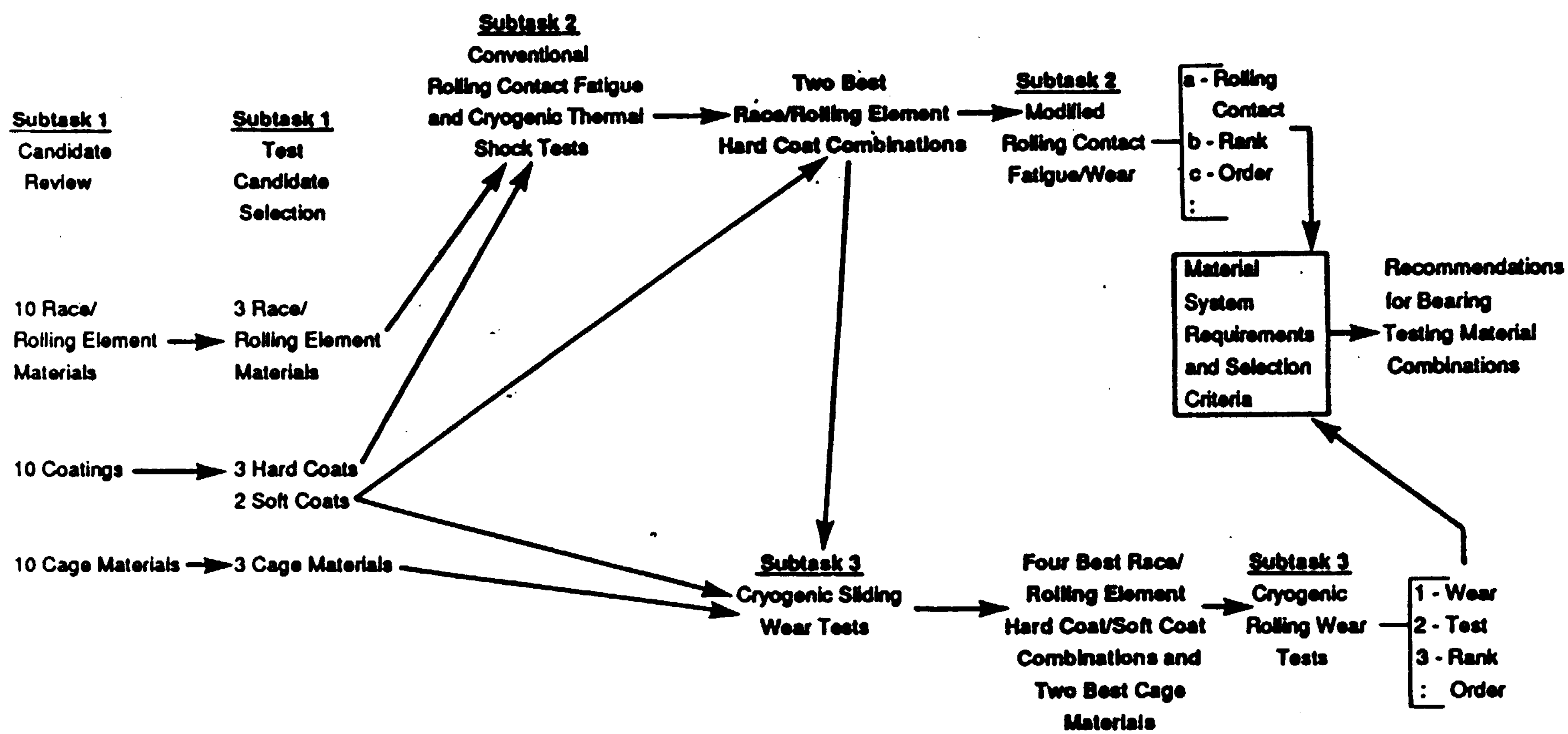
Bearing Materials Will Be Systematically Evaluated



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Preliminary Materials Have Been Selected For Evaluation

Race Rolling Element Materials	Hard Coats	Soft Coats	Cage Materials
440C (Baseline)	Ion Implantation Chrome	Ag	Armalon (Baseline)
CRB-7	Ion Implantation Titanium/Carbon	MoS_2	Salox-M
MRC-2001	PVD Cr 203		Silver-Plated Steel or Bronze

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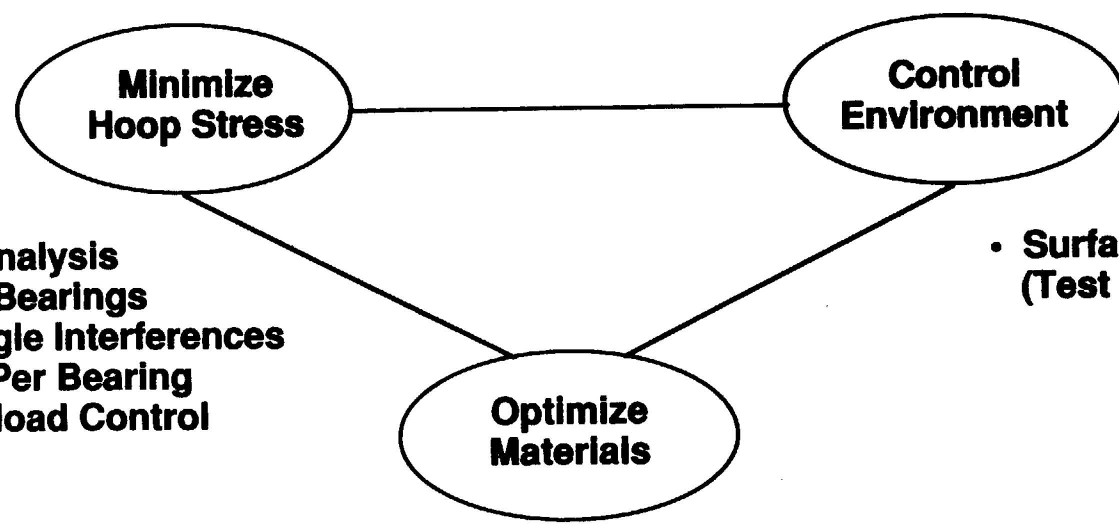
Multi-Pronged Approach to Stress Corrosion Cracking Issue



- Fit Analysis
- Ball Bearings
  - Single Interferences Fit Per Bearing
  - Preload Control

- Surface Treatment (Test Program)

- Forged Races (Test Program)
- Alternates (Test Program)
- Surface Treatment (Test Program)

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Casting Feasibility

- Phase I Impeller Development Program
  - Contact Industry Casting Leaders for Input on Facility Availability and Experience Base
  - Perform Mechanical Properties Tests on Vendor Supplied Coupons
  - Iteration of Casting Practice to Develop Best Mechanical Properties and Component Geometry
  - Destructive Tests of Castings for Metallurgical and Mechanical Properties Evaluation
  - Balance Tests to Verify Symmetry
  - Spin and Burst Tests to Determine Design Margins
- Phase II Casting Development and Refinement
  - Development and Refinement of Cast Impellers, Manifolds, and Housings

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Mechanical Properties Evaluation For Cast Components

Component	Material	Phase I	Phase II
Impeller	Ti-5Al-2.5 Sn ELI	T*, F*, CG*, Prolongation, Spin, Burst	Prolongation, Spin
Housing	Inconel 718	T, F, CG	Prolongation, Burst, Proof
Manifold	Incoloy 909	T, F, CG, SR*	Prolongation, Burst, Proof

*Preliminary Material Properties Evaluation, T - Tensile, F - Fatigue (LCF, HCH), CG - Crack Growth, SR - Stress Rupture

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Design Approach To Ensure Producibility

- Producibility Engineering Input to Design
- Casting Vendors Review Preliminary Drawings
- Tooling Options to Produce Casting are Considered
- Iterations to Refine Casting Procedures Have Been Included in Casting Program
- Modifications Made to Final Design to Ensure Reliability, Producibility, and Low Cost With Compromise to Performance if Necessary

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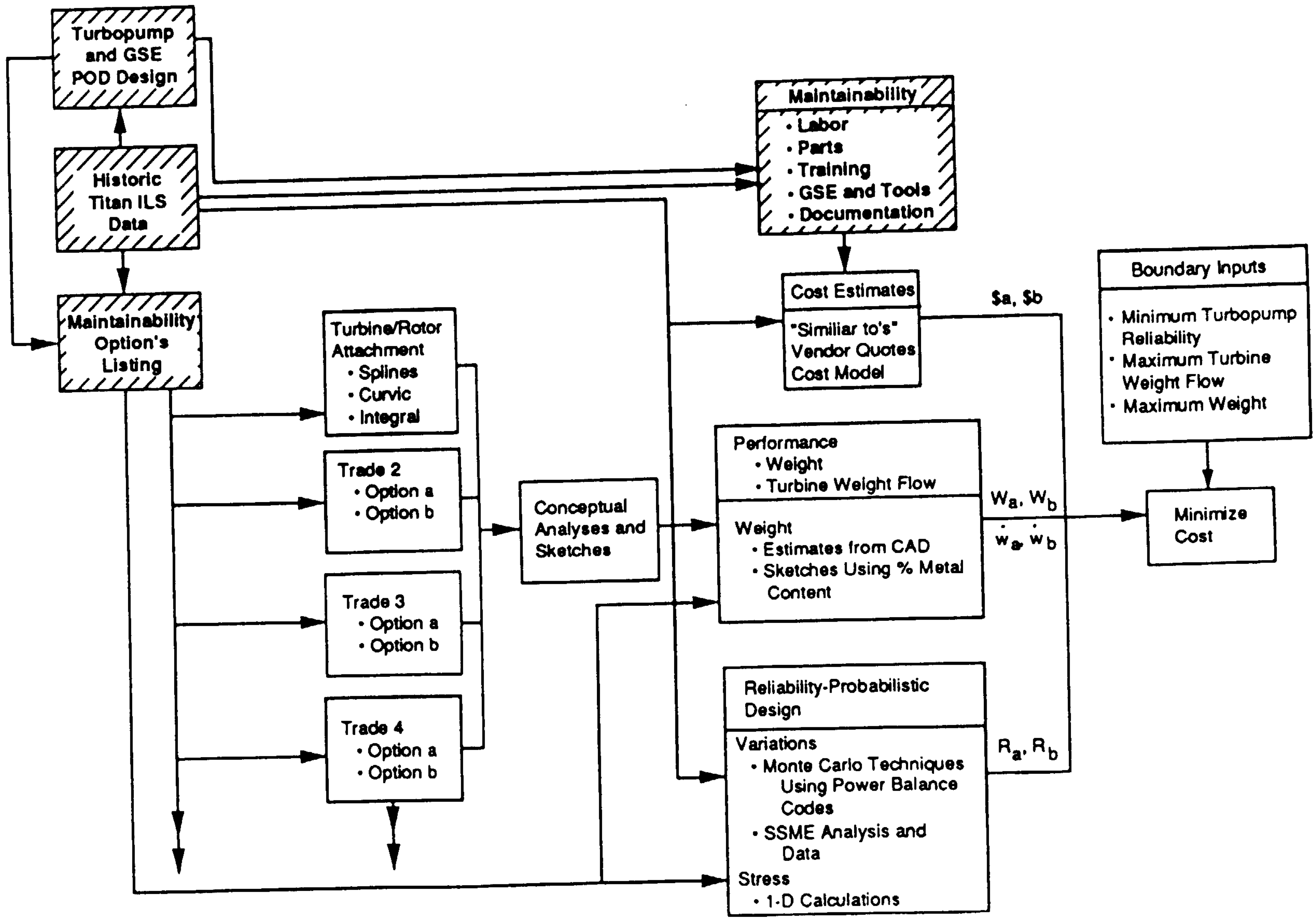
Parametric Analyses Will Be Used To Select Minimum Cost Design Configurations



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Trade Studies Will Be Used To Refine Our Low Cost Concepts

- Inputs
  - Part Costs
  - Part Weight
  - Relative Reliability
  - Turbine Weight Flow
- Constraints
  - Turbopump Reliability
  - Turbine Weight Flow Maximum ≈ TBD
  - Turbopump Weight Maximum ≈ TBD
- Optimize Configuration
  - ADS Code

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We Will Perform Design Trade Studies to Ensure a Reliable, Low Cost, Maintainable Design

	Options	Evaluation Parameters		
	Design Point Selection	Reliability	Cost	Performance
Design Concepts	Suction Specific Speed Limit SSS = 50,000	Higher Limits Decrease Tolerance to Variations	Lower Limits Increase Cost by Adding Weight but Reduce Costs by Increasing Life Expectancy	Higher Limits Improve Performance Due to Higher Turbine Efficiency and Reduced Weight
	Turbine Blade Stress Limit * $AN^2 = 25 \times 10^9$	Higher Limits Increase Turbine Blade Stresses		
	Bearing Speed, DN * $DN = 2 \times 10^6$	Higher Limits Decrease Bearing Load Capacity and Life		
	Impeller Tip Speed Limit U = 1800 fps	Higher Limits Increase Impeller Blade Stress		
	Turbine Tip Speed Limit * U = 1400 fps	Higher Limits Increase Turbine Disc Stress		
	Turbine Inlet Temperature * TTI =1140 degrees F	Higher Limits Reduce Reliability by Reducing Material Strength	Higher Limits Increase Cost by Limiting Material Choices	Higher Limits Reduce Turbine Weight Flow
	Turbine Manifold Casting * One Piece Casting Two Piece Casting with Bolted or Welded Nozzle Ring	Potential Leak Path Removed with Single Piece Casting or Welded Two Piece Casting	Commonality Reduced With One Piece Casting Since Nozzle Ring Not Removable. Assembly and Machining Cost Increase With Two Piece Casting	Bolted Flange Increases Weight
	Turbine Manifold Flange No Pressure Containment * Welded - Inseparable Bolted - Separable	Welding Increases Variability in Material Properties; Bolted Design Increases Thermal Stresses	Welded Manifold Increases Assembly Costs	Bolted Flange Increases Weight
	Turbine Rotor Shaft Attachment * Curvic Couplings Splines Integral	Evaluate Internal Friction Effect on Dynamic Stability; Critical Speed Windows	Evaluate Assembly/ Disassembly Costs	No Effect
	Impeller Shroud * Attached (Cast) Stationary (Back-up Only) (Machined)	Performance Variations Associated with Varying Tip Clearance on Stationary Shroud Design	Costs Penalties Associated With Machining	Stationary Design Has Tip Clearance Losses; Casting Surface Finish Lowers Efficiency
	Bearing Type * Ball Bearing Hybrids (Series Or Parallel) Hydrostatic	Ball Bearings - Life Limited Hybrids - Load Sharing Hydrostatic - Rubbing Start	Evaluate Assembly and Parts Costs for Each Concept	Evaluate Leakage Penalties With Each Type
	Pump Housing Material * Inconnel 718 Stainless 304L Titanium	Titanium Has a History of Cracking	Part Costs Increases Material Cost	Weight Increases as Strength-to-Weight Ratio is Reduced

* Selection for Point of Departure Design

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Maintainability Options Listing

	Options	Evaluation Parameters		
		Reliability	Cost	Performance
Maintainability	Breakaway Torque Movement • Turbine Driven - Cold Gas* • Mechanical - Wrench	With Mechanical, Leakage Potential in Access Port	Quantity Cost Differences; Launch Site Gas vs. Part Cost Increase	No Effect
	Turbine Blade Inspection • Best Method	Damage to Turbine Blades	Time to Gain Access vs. Inspection Time	No Effect
	Leak Check of External Connections • Pressure Between Dual Seals • Gas Chromatography • Bubble Check	No Effect	Quantity Differences	Weight Increase With Dual Seals
	External Seals • Dual Seals* • Single Seals	Increased Reliability With Dual Seals	Increase Part Cost With Dual Seals	No Effect
	Health Monitoring • Bently Probe for Bearing Distress	Increase in Bearing Life	Cost of Monitoring and Data Analysis	No Effect
	Vehicle Integration • Damage Rate Shipped, Installed, or Pulled from Engine	Likelihood of Undetected Damage	Damage Costs Assembly Costs	No Effect
	Method of Packing/Shipping	Likelihood of Undetected Damage	Damage Costs	No Effect
	Number and Types of Ground Support Equipment	Complexity and Interfaces	Acquisition and Launch Support Labor Costs	No Effect
	Number and Location of Pre-Flight Checkout	Increase Reliability Due to Additional Checkout; Reduce Breaking into System	Cost of Increased Manhours for Checkout	No Effect

* Selection for Point of Departure Design

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Commonality Provides Substantial Development and Life Cycle Cost Benefits

	Level	Options	Evaluation Parameters: Reliability	Cost - Development/LCC	Performance
Commonality	V	Common LCH_4/LH_2 TP 100%	LCH_4 TP Reliability Increases Because TP Operating Derated	Substantial Cost Savings	Significant Adverse TP Weight Impact on LCH_4 Pump
	V E	Common Turbine Manifold	Reliability Increase on LOX Pumps; Operating Derated	Identical on All 4 Turbopumps	Small Increase in Manifold Pressure Loss in LOX Pumps
	V E P	Common Turbine Rotor Discs	Margin Decrease on LOX Turbine Blades; Short Chord	Identical on All 4 Turbopumps and Stages Within Turbopumps	Performance Decrease On Fuel Turbines; Chord Length
	V E P	Common Impellers	No Effect	Identical Within Common Fuel Turbopumps	Lower Performance on 2nd Stage Due to Increased Incidence
	V E P	Common Bearings	LOX TP DN Higher Than for Optimized LOX TP but Greatly Derated from Fuel Conditions	Identical Within Turbopumps and Between Turbopumps	Increased Weight on LOX Pumps
	V E P	Common Lift-Off Seals	Increased Reliability - Improvement/ Experience Curve	Between Turbopumps	No Effect
	V E P	Common Fir Tree Attachment for Turbine Blades	Increased Reliability - Improvement/ Experience Curve	Between Turbopumps	No Effect
	V E P	Turbine Blade Dampers Coulomb Friction Tip Dampers	Increased Reliability - Improvement/ Experience Curve	Identical Within Turbopumps and Between Turbopumps	No Effect

Legend
V - Within Vehicle E - Within Engine P - Within Turbopump

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Results Of Low Cost Studies Will Be Incorporated In Baseline Design

- Update Preliminary Design Analyses
- Initial Reliability Estimates
  - Probabilistic Design
- Update Component Costs
- Tooling Concepts - Assembly/Disassembly
- Update GSE/Test Cart Concepts
- Begin Instrumented Design
- PDR

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Laboratory Tests
(W.B.S. 1.2.0)

George Claffy

Objective: Determine Feasibility of Selected Technologies

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Lab Tests Will Be Performed To Support Preliminary Designs

- Casting Feasibility
  - Material Characterization Tests
  - Impeller Spin Tests
- Turbine Blade Tests
- Bearing and Seal Tests
  - MTI Materials Tests
  - Stress Corrosion Cracking Test

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Key Issues Addressed In Test Programs

Materials Testing

- Cast Materials Have Insufficient Data Base for Our Applications
  - Incoloy 909 - HEE, High Temp. Fatigue
  - Ti - 5, 2.5 - HEE, Cryo Fatigue and Ductility
  - Inconel 718 - HEE, Cryo Fatigue and Ductility
- Additional Data Required on Turbine Blade Material
  - Therm., Mech. Processed (TMP) A-286 - HEE, High Temp. Fatigue

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Key Issues Addressed In Test Programs (Cont)

Impeller Fab and Test

- Feasibility of Casting Impeller Geometry to Net Shape
- Feasibility of Using Titanium Castings for High-Speed Rotating Component
  - Dimensional Uniformity
  - Distortion at Speed
  - Variability of Physical Properties Within Casting
  - Effect of Non-Uniform Cooling Rates on Microstructure
  - Cryogenic Ductility

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Key Issues Addressed In Test Programs (Cont)

Turbine Blade Fab and Test

- Feasibility of Forging Blade Geometry to Net Shape
- Sample-to-Sample Variability in A-286 TMP Material
  - Dimensions
  - Physical Properties
  - Natural Frequencies

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Key Issues Addressed In Test Programs (Cont)

Bearing/Seal Testing

- Selection of High-Reliability Bearing Materials
  - MTI Sliding/Rolling Tests Will Identify Candidates
  - Candidates Will Be Evaluated in ATC Test Unit Under Simulated Service Conditions
    - Speed
    - Loads
    - Cryogenic Fluid
- Demonstration of Lift-Off Seal Reliability
  - Operate in ATC Test Unit

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Tests Will Confirm Properties Of Critical Materials (WBS 1.2.2)

Objectives

- Evaluate Four Materials
  - Incoloy 909 Cast - Verify HEE and High Temperature Properties
    - Stellite 31 (Backup for Incoloy 909)
  - Inconel 718 Cast - Verify HEE and Cryo Temperature Properties
  - Ti 5, 2.5 Cast - Verify HEE, Ductility at Cryo Temp, Uniformity of Properties
  - TMP A-286 - Verify HEE and High Temperature Properties

Approach

- Perform Tests in Simulated Environments
  - HEE - Aerojet Hydrogen Materials Test Facility
  - Turbine Materials - 1200°F Simulated Combustion Gas
  - Pump Materials - LH_2

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Materials Tests Address Needs Of Specific Components

Material	Principal Component(s)	Tests: Tensile	Fatigue	Crack Growth	Stress Rupture
Incoloy 909 (Cast)	Turbine Hsg.	R, G, H, E	R, G, H, E	R	E, G
	Turbine Vanes				E, G
A-286 TMP (Forged)	Turbine Disk	R, G, H, E	R, G, H, E		
Ti-5, 2.5 (Cast)	Pump Impellers	R, C, H	R, C, H	R, C	
Inconel 718 (Cast)	Pump Hsg.	R, C, H	R,	R	

R = Room Temperature

E = Elevated Temperature

C = Cryogenic

G = 1200°F Gas

H = HEE (R.T.)

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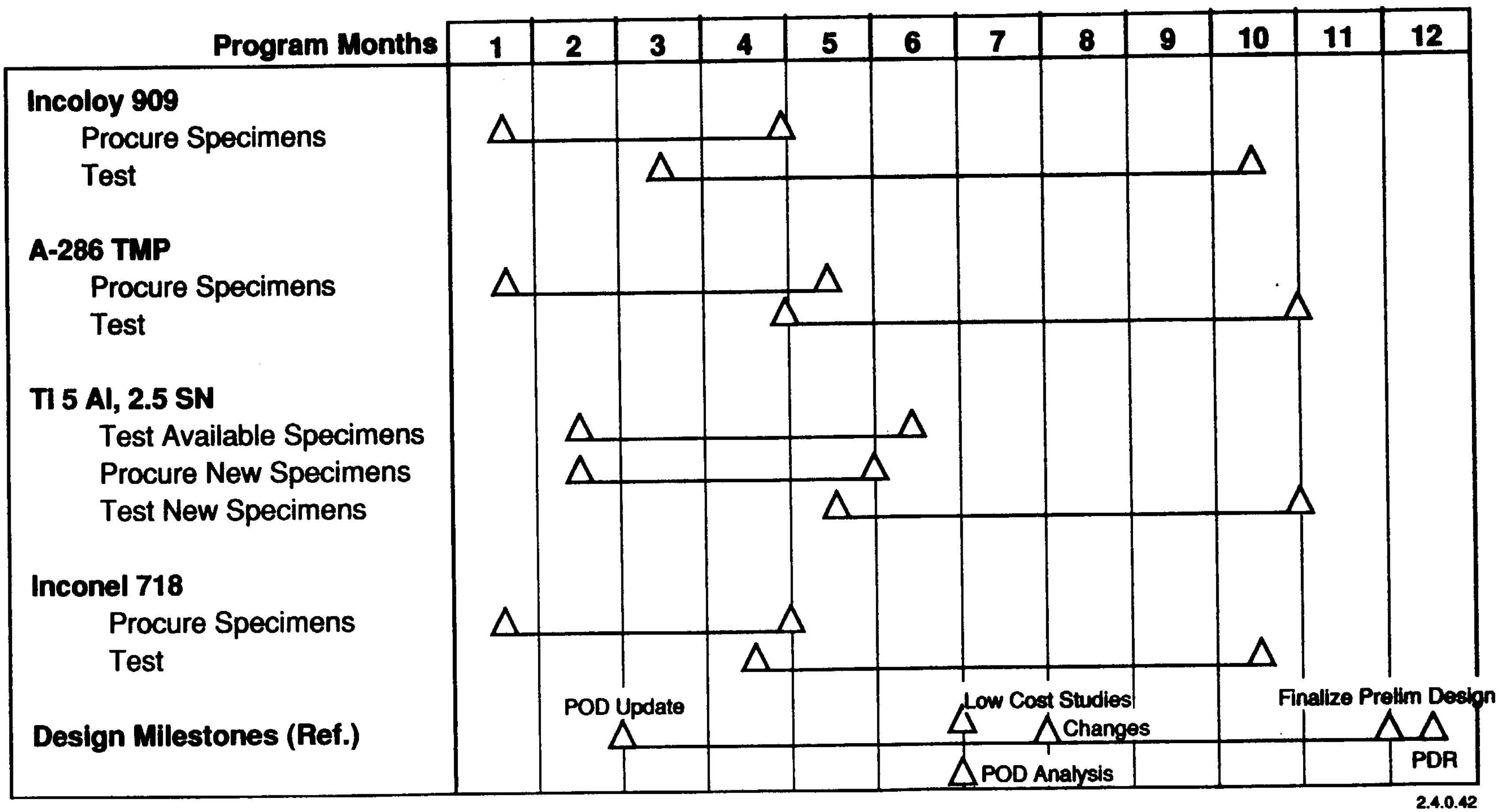
Materials Testing Schedule Supports Preliminary Design



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Feasibility Of Casting Pump Impellers Will Be Evaluated (WBS 1.2.4)

Objectives

- Develop Tooling and Process for Casting Ti Pump Impellers for ALS
- Produce Several Castings to Demonstrate Repeatability
- Evaluate Structural Integrity by Testing

Approach

- Prepare Preliminary Casting Drawing for Representative Pump Impeller of Ti 5, 2.5
- Prepare Tooling and Pour Trial Pieces. Iterate Tooling and Drawing Based on Results
- Pour Additional Cast Impellers for Testing
- Machine Interfaces for Spin Testing
- Evaluate Structural Integrity by Metallurgical Testing and Spin Tests - Spin One Impeller to Burst

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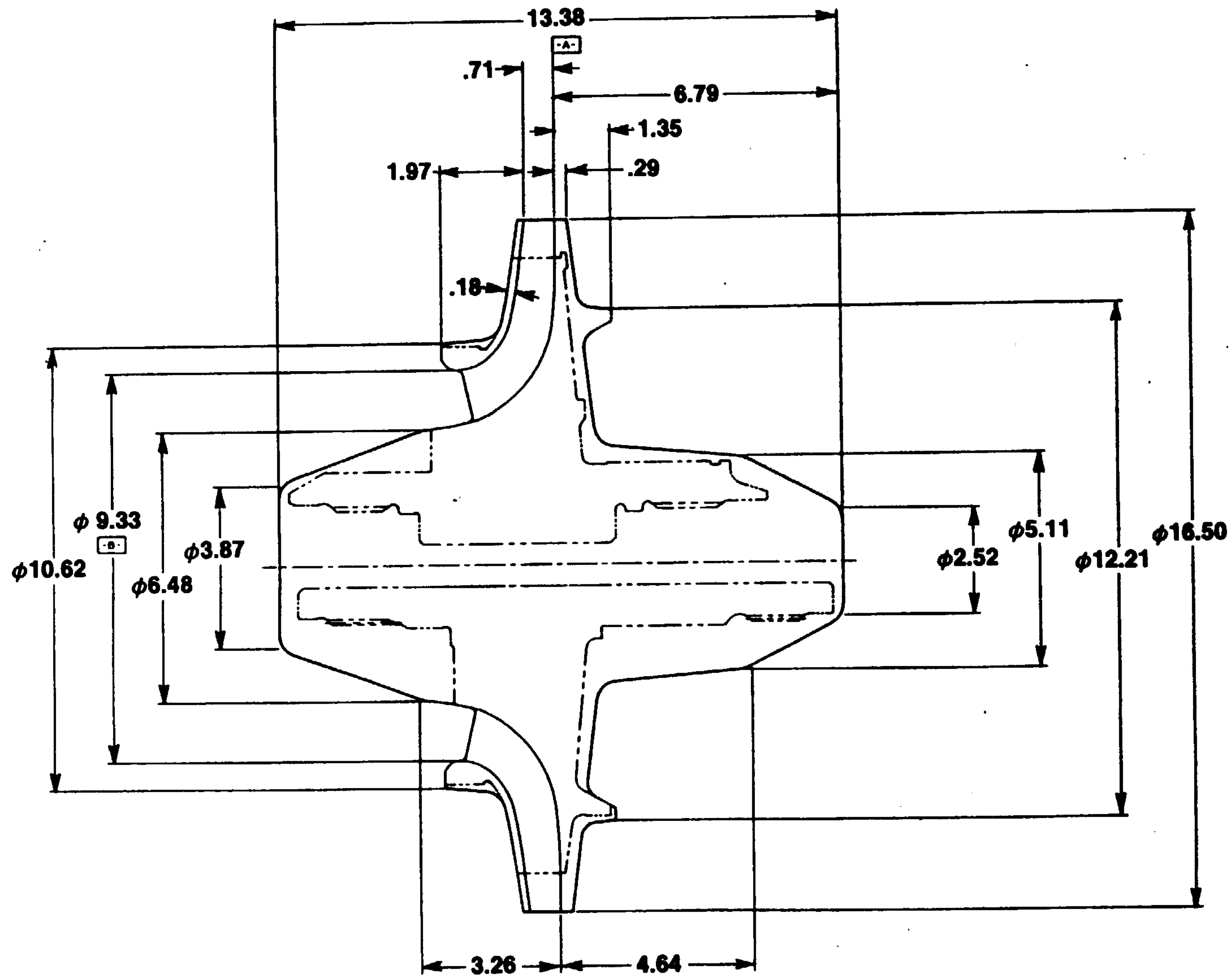
Casting CAD Drawing For Titanium Impeller Is In Progress



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Impeller Testing Will Provide Confidence In Cast-Titanium Structural Integrity

- Metallurgical Tests
  - Machine Specimens From Critical Areas of Sectioned Casting to Provide Data on Microstructure and Properties

- Spin Tests
  - Take One Impeller to Burst Speed for Comparison With Value Predicted for Assumed Properties and Dimensional Uniformity
  - Spin Remaining Impellers to Maximum Operating Speed With Strain Gages Incorporated, as a Check on Unit-to-Unit Variations
  - Spin Tests at Cryogenic Temperature Are Desirable. Now Investigating Means of Accomplishing This

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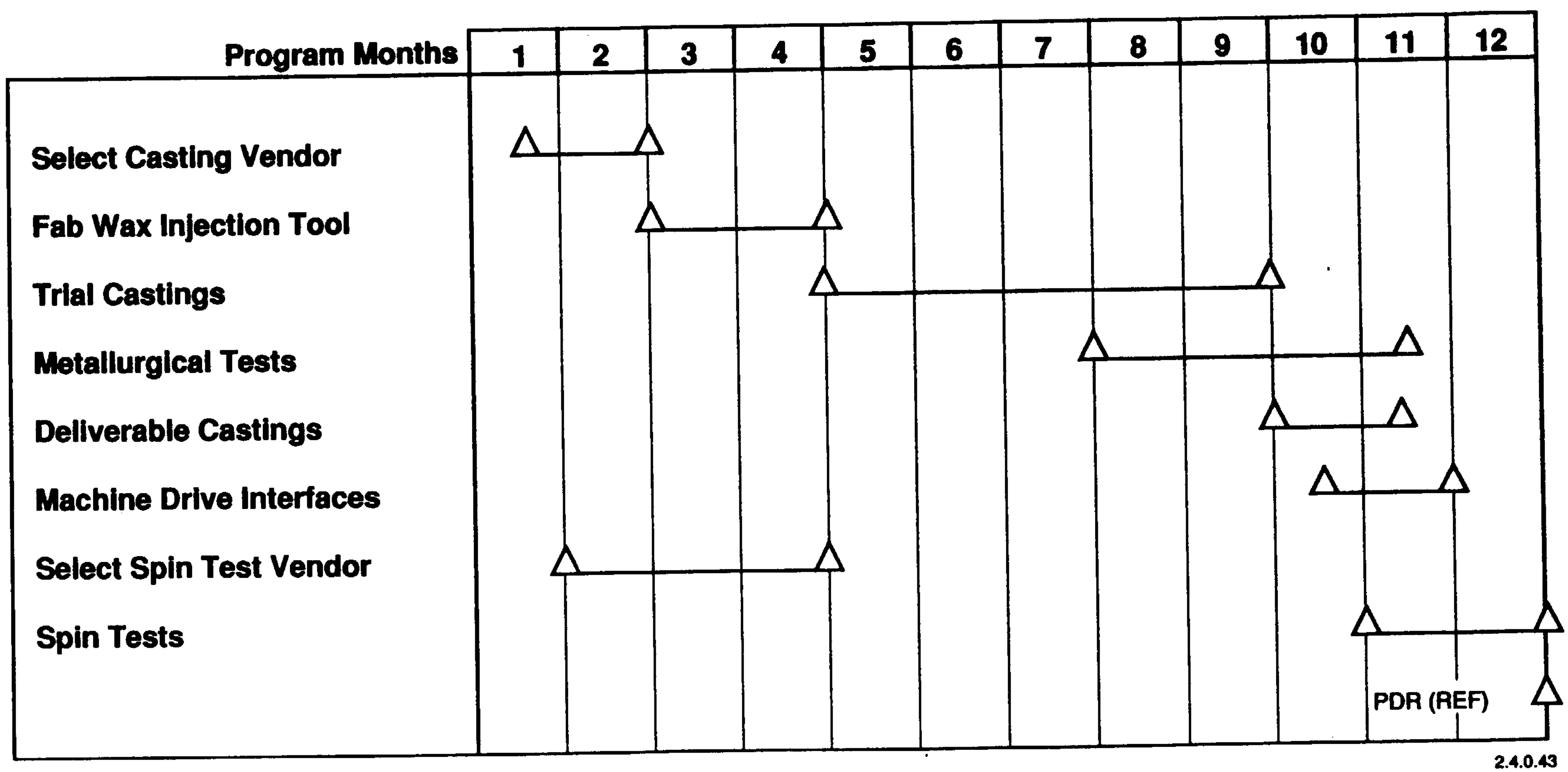
Impeller Testing Schedule Supports PDR



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Turbine Blade Test Approach Keyed To Analytical Results

- Blade Design Goal Is for All Natural Frequencies to be Above Blade Passing Frequency

- If There Is Insufficient Analytical Margin, a Vibration Survey Will Be Performed on Development Blades to Confirm Predicted Natural Frequency

- In Keeping With Good Design Practice, Dampers Will Be Incorporated During Detail Design—Assuming the Added Tip Mass Does Not Compromise Structural Integrity

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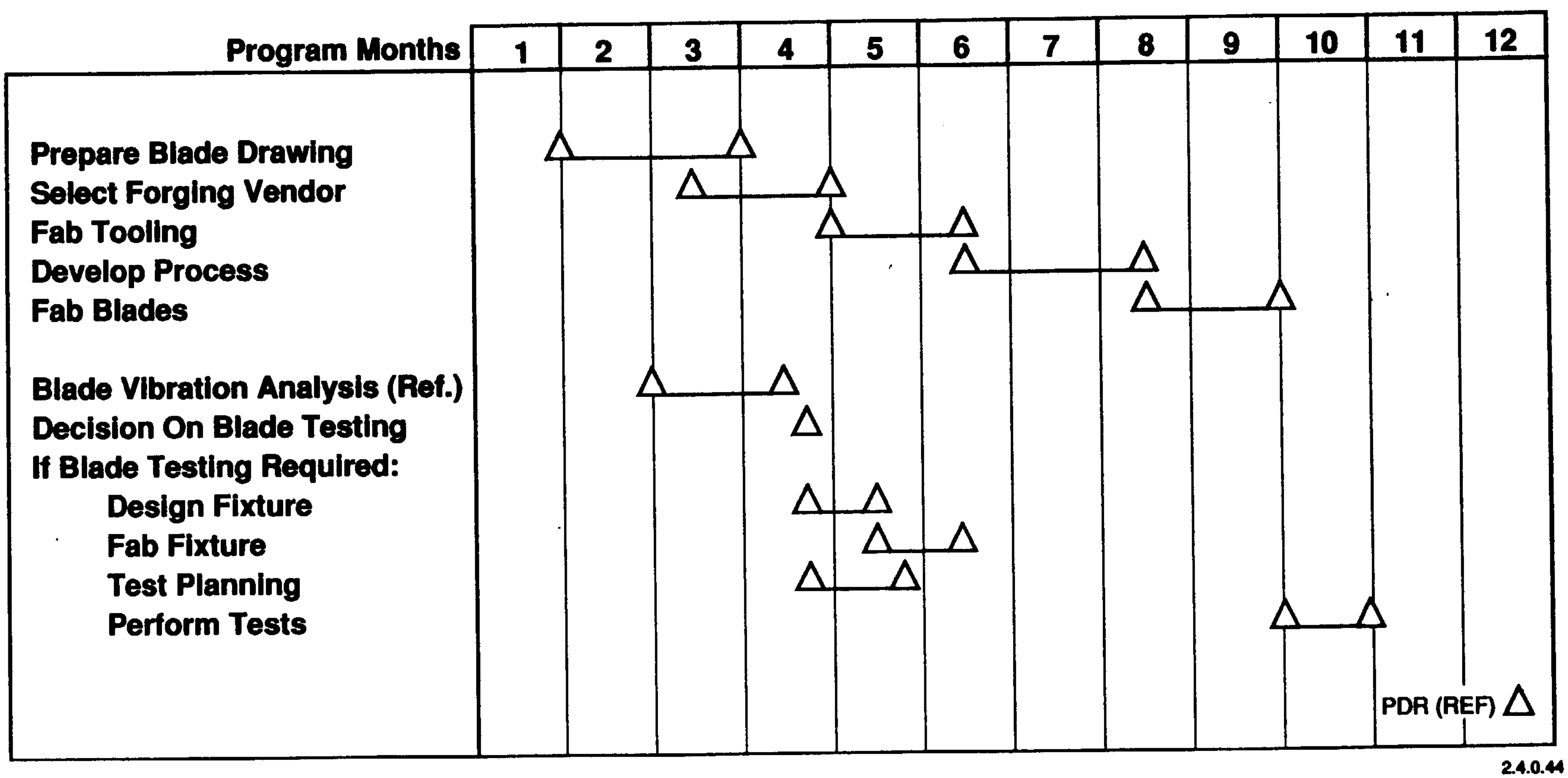
Turbine Blade Program Schedule Supports PDR



Bearing/Seal Test Preparations Will Assure Readiness For Phase II Testing (WBS 1.2.3)

Objectives

- Evaluate Baseline and Alternative Ball Bearing Materials/Configuration

Approach

- Utilize Existing Tester Design and Generic Parts
- Fab All Tester Hardware in Phase I
- Prepare Bearing/Seal Test Plan
- Select Test Facility

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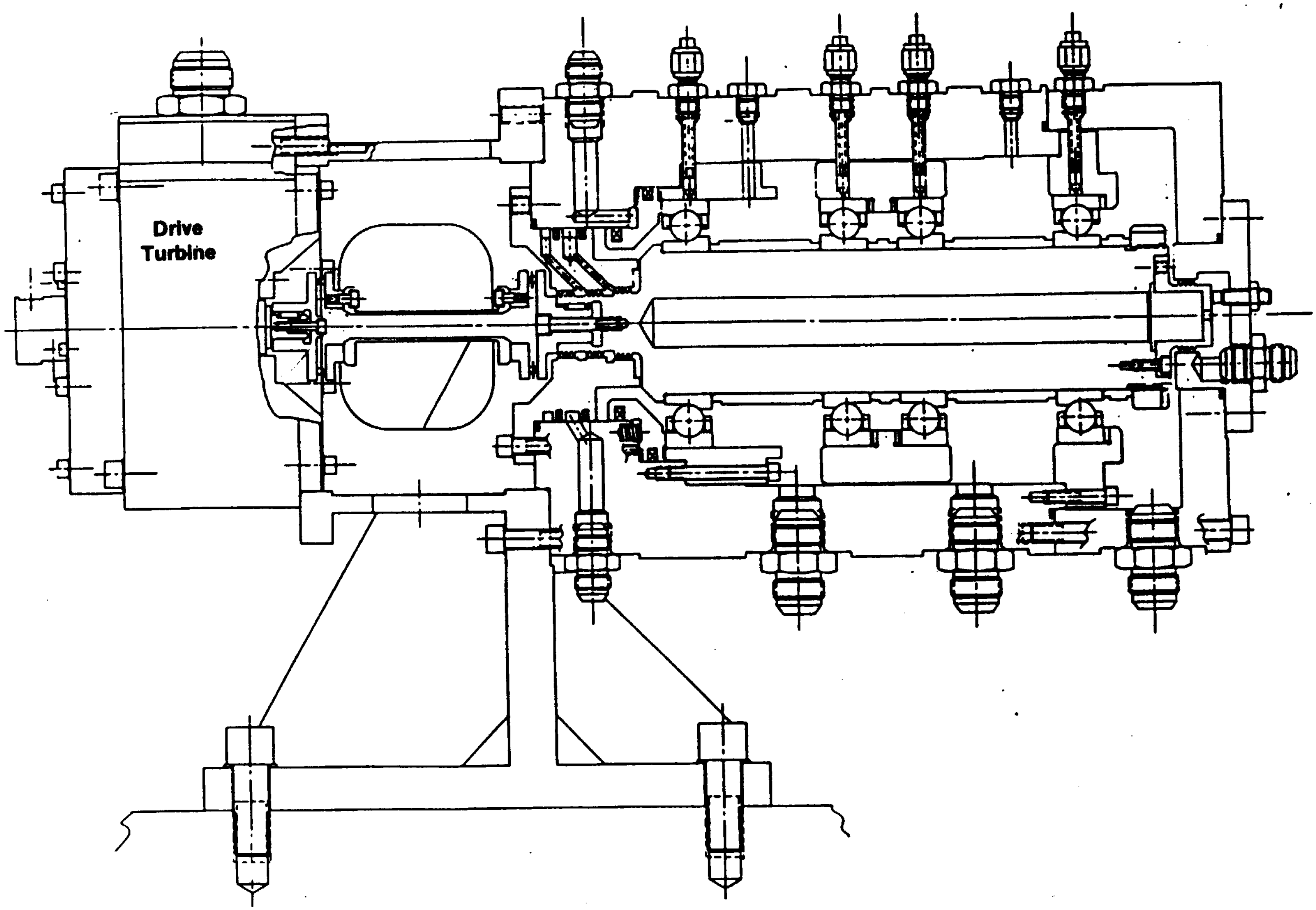
Bearing/Seal Test Configuration Has Been Defined



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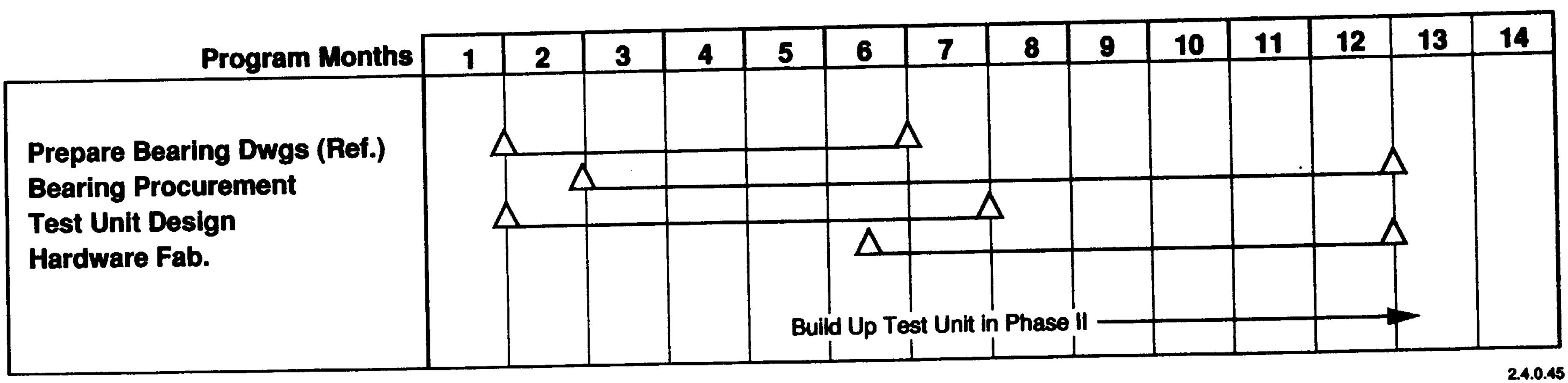
Brg/Seal Test Preparation Schedule Leads to Early Phase II Test



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Technology Development Plan (WBS 1.3.0)

- Provides Vehicle for Identifying Technology Areas in Need of Further Pursuit
- Anticipate Awareness of Technology Development Needs
- Sufficient Documentation Will be Provided to Support ALS Phase C/D Planning
  - Problem Statement
  - Data Required
  - Recommended Approach
  - Suggested Facilities/Equipment
- One Program Already Identified for Inclusion
  - Extended A-286 TMP Turbine Blade Life

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Preliminary Cost Model

Colin Faulkner

Objective: Develop and Anchor Cost Model

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Phase I Cost Model Deliverables

- Model Architecture (Preliminary Version)
  - Assumptions Used
- Input Data Sources
- Approach for Evaluating NASA Requirements Impacts
- Approach for Application of Phase II Fabrication Data
- Model Results Uncertainties Identified

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Cost Model Basis

- Piece-Part Based
  - Process Flows Developed for Each Part and Assembly
  - Production and Operations Activities
  - Specifications and Procedures Identified for Each Flow Activity
- Spreadsheet Based
  - Records and Manipulates Data (Learning Curves, etc.)
- Titan Data Base
  - Titan Production and Operations Costs Anchor Initial Model and "Test for Reasonableness"

Program Goal: Reduce Magnitude of Cost Uncertainties
Today: 20-30% (STME/STBE Studies)
Phase II End: 5-10%

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O&S Costs Will Be Addressed

- O&S Costs Will Be Estimated Using:
  - Historical Data Base
    - Titan 1st and 2nd Stage
    - SSME
    - Defense Logistics Agency Reports
  - Analysis
    - Detailed Evaluation of Activities
- Estimates at Maintenance Significant Item (MSI) Level
- Estimates Will Include Mission Model, Launch Rate, Service-Free Life, Useful Life, Turnaround Time
- Apportion Propulsion System Level Costs to Component Assembly Level

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Specifications And Procedures Impacts Analysis

- Concurrently Optimize Design, Fabrication, O&S and Specification Requirements
  - — Specifications Analyzed as Up-Front Activity
  - — Zero-Base Budget Approach
  - — Verify Need for Each Specification Item
  - — No Specification Duplication
  - — Design to Avoid Sensitive Production Processes
  - — Develop Simplified Specification Where Possible
  - — Tailor Government Specifications or Substitute Contractor Specifications

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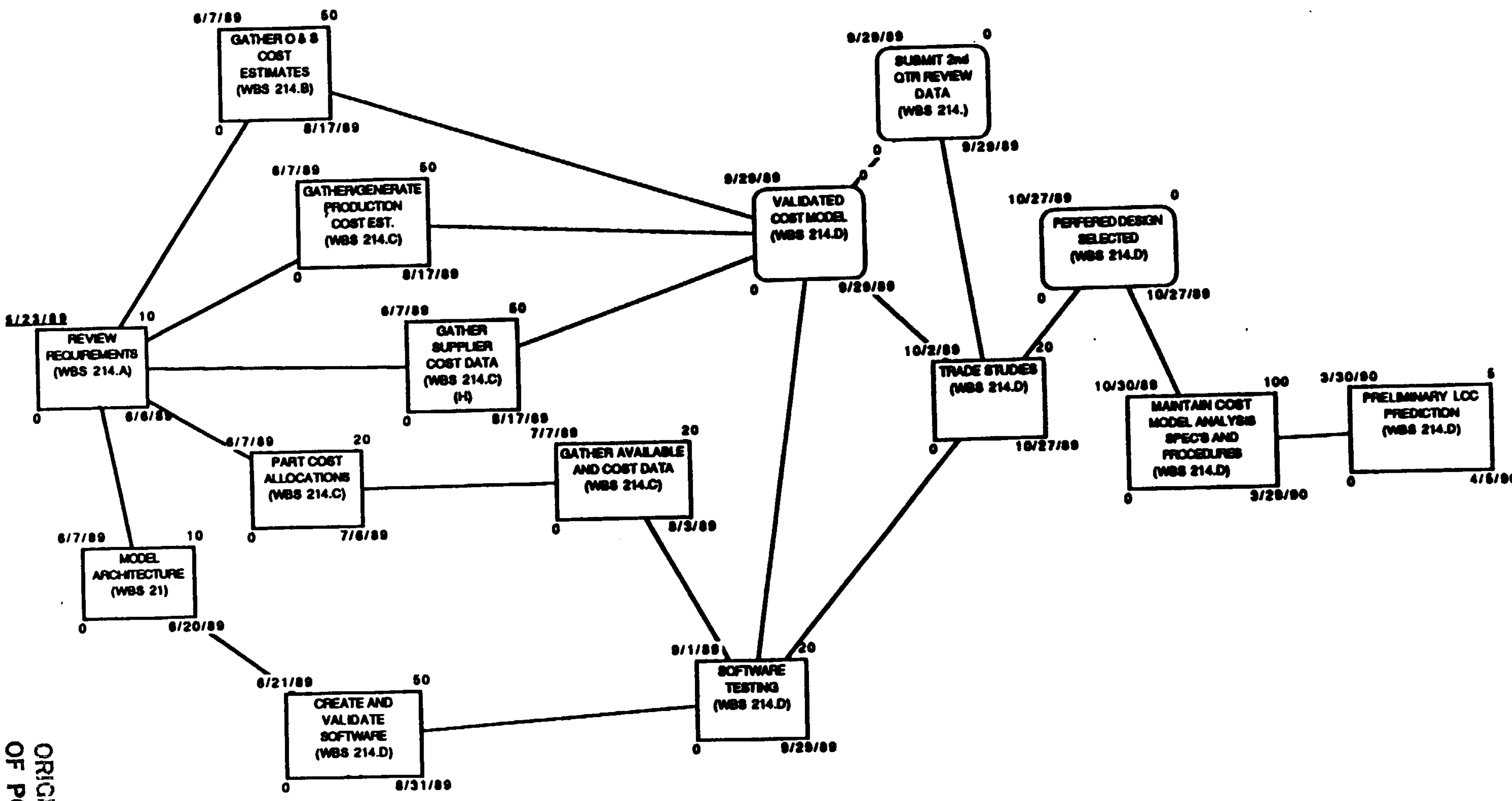
Phase I Cost Model Network/Schedule



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Phase II

Detail Design, Fabrication, And Test

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Phase II Focused On Turbopump Fabrication And Test

- Detail Design
  - Producibility Trades
  - Drawings
  - Supporting Detailed Analyses
- Experiments
  - Bearing Life Testing
  - Seal Development
- Fabrication
  - Fabrication of Two Turbopumps
  - Proof Testing
  - Inspection Technique Development
- Testing
  - Cold Gas - Internal Environment
  - Hot Fire - Full Load
- Cost Model
  - Data Base Development

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Detail Design
WBS (2.1.0)

Objective: To Produce All Drawings With Supporting Analyses Required to Make the Two Turbopumps

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Detail Design Will Re-Emphasize Producibility

- Producibility Refinements
  - Casting Options
  - Inspection Techniques
  - Production Enhancers for Cast Parts
  - In-Process Controls
    - MTI
    - Ingersoll
  - In-Process Inspection
    - MTI
  - Factory Floor Optimization and Organization
    - Ingersoll Engineering
  - High Speed Balance
    - MTI

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We Will Perform Trade Studies to Enhance Design Producibility

	Options	Evaluation Parameters: Reliability	Cost	Performance
Production Options	Casting Technique Pump Housing and Turbine Manifold • Investment * • Sand	Investment Results in Less Variability	Quantify Savings With Sand Castings	Efficiency Penalties From Surface Roughness With Sand Castings
	Slurry Polishing • Pump Diffuser Vanes • Turbine Nozzles • Crossovers	No Effect	Quantify Cost Increases, Combine with Sand Castings	Efficiency Benefits From Improved Surface Roughness
	Inducer • Machined from Billet * • Cast With Machined Leading Edges	No Effect	Quantify Cost Differences	No Significant Impact
	Production Enhancers Study for Cast Parts			
	• Hydro/Leak Check With Clamps Before Machining • Casting Targeting * • CAD/CAM/CAE • X-Ray or Spin Verification of Part Integrity • In-Process Controls * • NDE/Dye Pen	No Effect Less Part-to-Part Variations Less Part-to-Part Variations No Effect Less Variation in Material Properties Quantity Effects	Quantify Cost Benefits	No Effect
	• In-Process Inspection for Machined Parts Including Electro-Optical Sensors (MTI) *	Less Part-to-Part Variations	Part Rejection Rate, Inspection Costs, Capital Expenditures	No Effect
	Factory Floor Optimization * • Work Cells • Material Handling • Lead Time • Inventory, Just-in-Time • Assembly • Interface with Suppliers (Ingersoll Engineering)	No Effect	Determine Optimum Combination for All Parts; Capital Expenditures	No Effect
	High Speed Balance (MTI)	Rub Risk Reduced Bearing Loads Reduced	Quantify Balancing Costs	No Effect

* Selection for Point of Departure Design

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Detail Design Provides Drawings For All Equipment Required For Testing At SSC

- Hot Fire Turbopump
  - Supporting Analyses
  - Long Lead Release
  - Probabilistic Design of Life Drivers
  - Assembly Manuals/Tooling Drawings
  - Test Plans

- Cold Gas Turbopump
  - Long Lead Release
  - Assembly Manuals/Tooling
  - Test Plans

- Reliability Predictions

- Test Cart

- GSE

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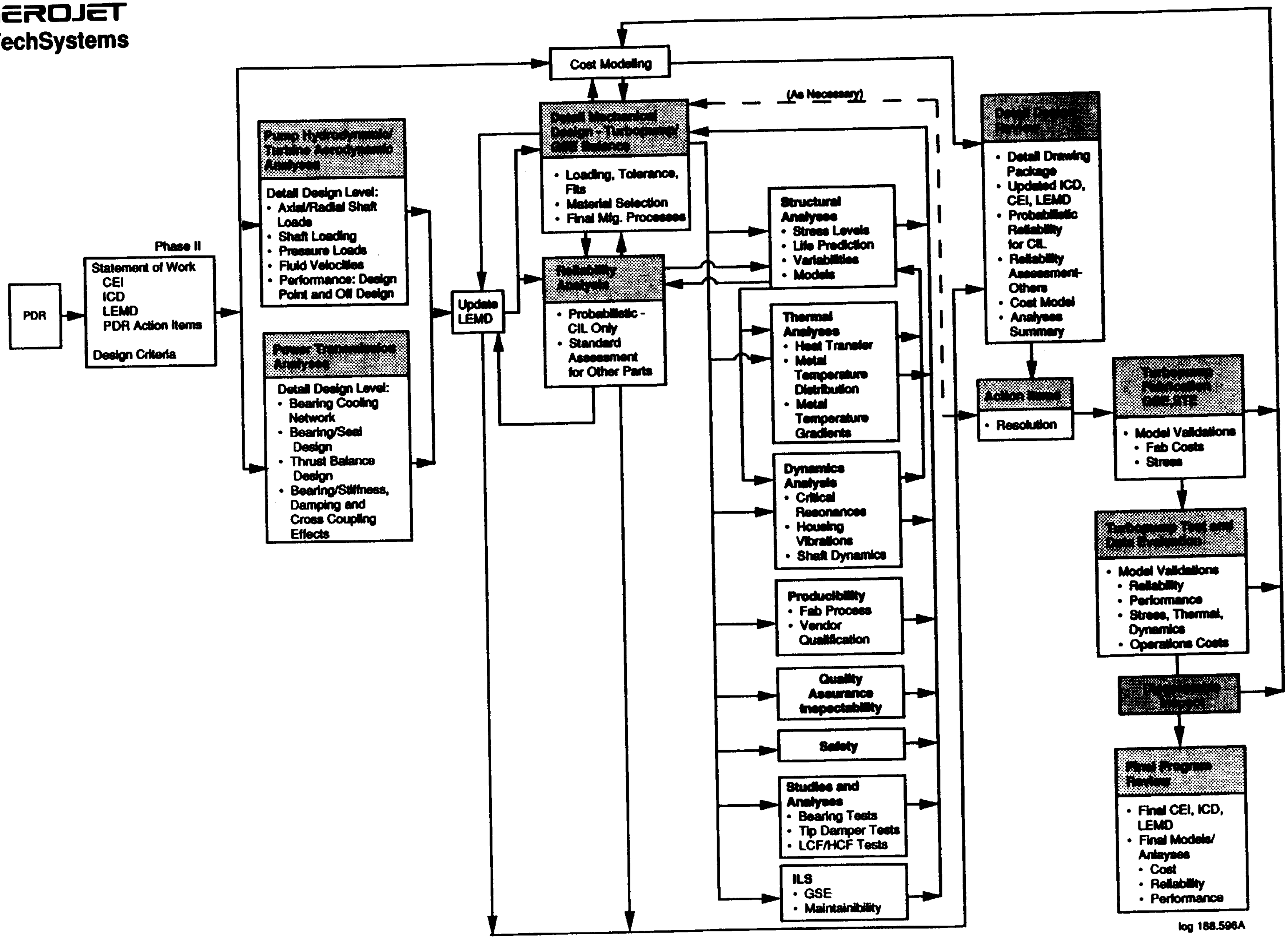
Phase II Detail Design and Analysis Methodology



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During Detail Design, Additional Technology Development Will Be Identified

- Materials Characterization Plan
- Analytical Model Development Plans
- Technology Development Plans
  - Titanium Housings
- Instrumentation Requirements

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Phase II Laboratory Testing Supports Detail Design (WBS 2.2.0)

- Bearing and Lift-Off Seal Test
  - Substantiates Designs of These Elements
  - Provides Ranking of Bearing Material Combinations
    - — Baseline: 440C/Armalon
    - — Alternative: TBD
  - Operate in Cryogenic Fluid at Rated DN
  - Applied Bearing Loads 100% - 150% of Predicted Values
  - Will Run Duty Cycle Simulating Mission Operation
  - All Hardware Fab and Test Planning Accomplished in Phase I

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Bearings and Lift-Off Seal Will Be Rig-Tested

LH_2 TPA 75mm Ball Bearing and Lift-Off Seal Test Plan

Test Series	No. of Tests	Duration (Sec)	Bearing Fluid	Bearing Pressure and Flow Rate	RPM	Test Objectives
Checkout	4	15-30	LN_2	300 psi/ 100 gpm	10,000	Ensure Proper Operating Conditions, Including Instrumentation and System Integrity
Start/Stop and Endurance Test	15	540	LH_2	300 psi/ 100 gpm	26,700	Evaluate Life Versus Wear of Ball Bearings and Cage Designs
Bearing Inspection	-	-	-	-	-	Measure Ball Diameters and Races for Wear; Inspect for Cracks

Notes:
- Flow Past Lift-Off Seal Will be Monitored; Also Lift-Off Seal Axial Position Will be Measured.
- Approximately 100-150% Design Radial and Axial Loads Apply to Bearings.
- Existing Facility Drive Turbine Will be Used.
- GN_2(50-150°F @ 50 psia) Will be Used as Drive Gas.

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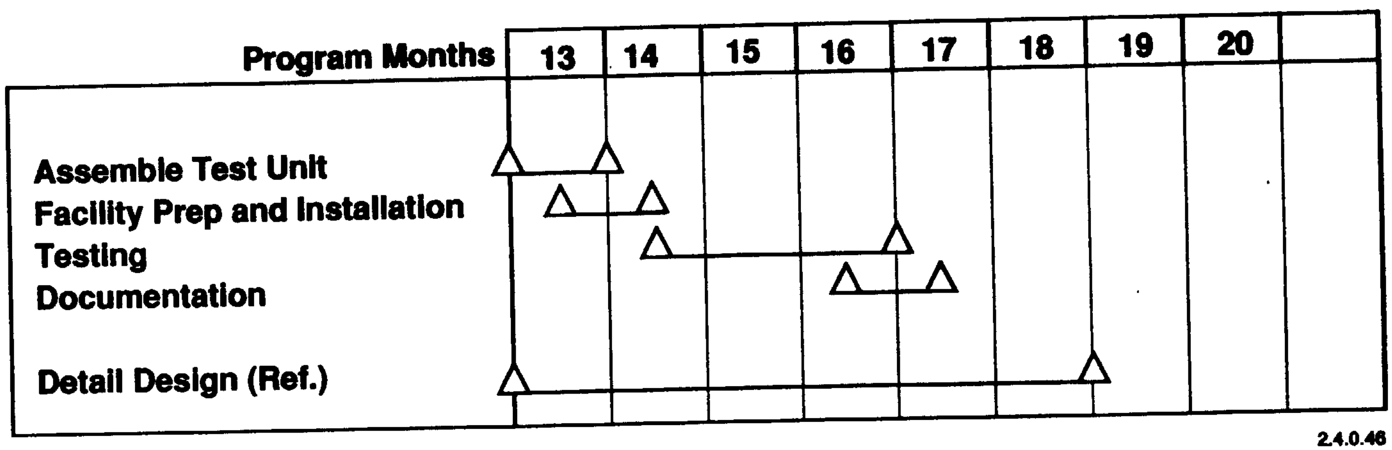
Brg/Seal Test Schedule Supports Detail Design



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Turbopump Fabrication And Testing

G. Claffy

Objective: Fab, Assemble, and Test Two Turbopumps

Prototype Turbopump Fabrication Will Support Test Program And Calibrate Models (WBS 2.3.0)

- Long Lead-Approval Needed by Month 16
- Supplier Screening and Selection
- GSE/STE Detail Design and Fab
- Procure/Fab Hardware for Two Turbopumps Plus Critical Spares Plus Assembly Tooling

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Prototype Turbopump Fabrication Will Support Test Program And Calibrate Models (WBS 2.3.0) (Cont)

- Inspection/QA
  - Acceptance Plan (DR-20) - Month 19
  - Acceptance Data Package (DR-31) - Month 32
  - Acceptance Review - Month 34
- Assemble and Deliver Two Turbopumps
- Collect Cost Data/Calibrate Cost Model
- Develop Key Procedures
  - Assy/Teardown
  - Balancing
  - Casting Inspection
  - Transportation/Storage

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Summary of Deliverable Hardware

Unit 01-Cold Gas/Instrumented Turbopump	1
Unit 02-Hot Gas/Instrumented Turbopump	1
Critical Item Spares:	
Impeller	2
Pump Housing	1
Turbine Manifold	1
Turbine Exhaust Housing	1
Turbine Rotor Assembly	2
Bearings	8
Seals	misc
GSE	
(Subject to Change, Based on Test Cart Design):	
Handling Fixture	1
Maintenance Stand	1
Closure Kit	1
Shipping Container	1
Portable Crane	1
Work Table	1
Pallet Mover	1
STE:	
Pump Discharge Line	1
Turbine Inlet Line	1
Test Cart	1

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Major Fabrication Milestones Are Established

- Long Lead Item Detail Design and Fab Release - Month 16
- All Detail Drawings Complete, Released for Fab - Month 21
- Hardware Fab and Proof Testing Complete - Month 32
- Test Units Assembled, Delivered, and Installed at SSC - Month 34
- GSE/STE Fab Complete - Month 32

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Phase II Turbopump Test Effort Includes Planning, Support, And Analysis (WBS 2.4.0)

- Test Plan Draft (DR-30) Prepared Concurrent With Detail Design
- Critical Experiment Review Will Include Finalized Test Plan
- ATC Personnel Will Support Turbopump Installation and Test, and Perform Data Analysis/Evaluation
  - Installation, Maintenance, and Removal Data Will Be Closely Monitored and Documented (DR-33) for Cost Modeling Inputs
- Test Results Report Will Be Prepared After Conclusion of Testing (DR-34) Including Reliability Update
- Turbopump Will Be Disassembled and Inspected After Testing

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Key Test Objectives Defined for Cold-Gas Test

Key Parameter Measured	Type Instrumentation Required	Overall Objectives
Steady/ Unsteady Blade Pressure Loading	• High Freq. Mininature Press. Transducers • Strain Gages	• Linearized Theory and CFD Rotor Stator Interaction Unsteady Pressure Oscillation Predictions • Update Probalistic Analysis and Loads/Environment Document
Rotor & Stator Study & Dynamic Blade Stresses	• Strain Gages	• Stress Models • Update Probabalistic Analysis and Loads/Environment Document
Bearing Radial Load	• High Freq. Pressure Transducers	• Calibrate CFD Models of Pump Volute and Turbine Inlet • Update Probabalistic Analysis and Loads/Environment Document
Shaft Axial Thrust	• Pressure Transducers • Proximity Gages	• Calibrate CFD Models of Impeller Front & Rear Shroud Cavities Balance Piston Cavities, and Turbine Disk Cavities • Update Probabalistic Analysis and Loads/Environment Document
Bearing/Seal Operating Environment	• Pressure Transducers • Flow Meters • Temp. Sensors	• Calibrate Local CFD Models and Overall Bearing Cooling Scheme Model • Update Probabalistic Analysis and Loads/Environment Document
Turbopump Performance	• Pressure Transducers • Flow Meters • Temp. Probes • Speed • Torque Measurement	• Verify Pump and Turbine Performance Predictions

Cold-Gas Turbopump Preliminary Test Matrix

Test No.	Pump (Q/N)/ Q/N) des	N/ N des**	Turbine (U/C)/ (U/C) des	Turbine PR/ PR des	Turbine Inlet Pressure (psi)	Turbine Discharge Pressure (psi)	Pump Discharge Pressure (psi)	Turbine Mass Flow (lbm/s)
1	1.0	0.5	2.38*	1.0	889	207	803	117
2	1.0	0.72	3.43*	1.0	3200	744	1665	421
3	1.1	0.72	3.43*	1.0	3200	744	1582	421
4	0.8	0.72	3.43*	1.0	2880	670	1830	379
5	0.8	0.5	2.38*	1.0	800	186	883	105
6	1.0	0.21	1.0	1.0	78	18	142	10

*2nd Stage Removed for Improved Performance at High U/Lo
**Planned test speed may be adjusted after critical speed analysis

Key Test Objective Defined For Hot-Gas Test

Key Parameter(s) Measured	Type Instrumentation Required	Overall Objective
• Operating Environment	• Pressure Transducers • Flow Meters • Speed • Temp. Probes	• Functional Validation in Real Engine Environment • Verification of Probabilistic Design Analysis and Reliability Predictions
• Performance	• Speed • Pressure Transducers • Temp. Probes	• Verification of Performance Scaling
• Rotordynamic Behavior	• Proximity Probes • Accelerometers	• Verify Dynamic Response Characteristics

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Hot-Gas Turbopump Preliminary Test Matrix

Test No.	Pump (Q/N)/ Q/N) des	N/ N des*	Turbine (U/C)/ (U/C) des	Turbine PR/ PR des	Turbine Inlet Pressure (psi)	Turbine Discharge Pressure (psi)	Pump Discharge Pressure (psi)	Turbine Mass Flow (lbm/s)
1	1.0	0.7	0.7	1.0	780	186	1589	21.7
2	1.0	1.0	1.0	1.0	1755	418	3211	48.8
3	0.8	1.0	1.0	1.0	1580	376	3529	43.9
4	1.1	1.0	1.0	1.0	1843	460	3052	51.2
5	1.0	1.0	1.0	1.0	1755	418	3211	48.8
6	TBD							
7	TBD							

*Planned test speed may be adjusted after critical speed analysis

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Detailed Cost Model

Colin Faulkner

Objective: Develop a Verified Data Base for the Cost Model

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Phase II—Cost Model Deliverables

- Completed Detailed Cost Model
  - Structure Description
  - Construction Assumptions
  - Input Data Sources
  - NASA Requirements Impacts
- Flight Hardware Cost Estimates
  - Theoretical First Unit Cost
  - Recurring Production Costs (Learning Curve and Rate Effects)
  - Recurring Operations Costs
- Cost Estimate Substantiation
  - Historical
  - "Similar TOS"
  - Phase I and II Fabrication
- Independent Assessment Weights
  - Parts and Assembly Weights
  - Complexity
  - Precision
  - Materials

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Multiple Approaches To Reduce The Magnitude Of Uncertainties

Uncertainty	Approach
Piece Part Costs	• Prototype Build • Quotes From Multiple Vendors • Touch Labor and Touch Inspection
Learning Curve Effects Lot Size Effect	• Vendor Quotes on Lot Size and Quantities • Historic Data
Productivity	• Historic Data — Scrap, Rework and Repair — Tooling, and Tool Maintenance • Documented Productivity Improvements — Historic Data — Consultants - Ingersoll Engineering - MTI

• Uncertainty Values Are Allocated to Each Piece Part

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Emphasis On Production And Operations Costs

- Audit Manufacture of Test Articles at Piece Part Level:
  - Two Turbopumps
  - Test Cart
  - GSE
- Analyze Applications of Advanced Factory Organization, Layout, and Equipment
  - Ingersoll Engineering
  - MTI
- Audit Test Operations at SSC:
  - Test Cart (Projected Acceptance Test Costs)
  - Operation and Maintenance of Turbopumps (Simulated Launch Pad Conditions)
- Audit Specifications and Procedures Impacts
  - Manufacture
  - Operations
  - Tom Peters Group Contributes Unbiased Perspective

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Launch Rates and O&S Costs Are Covered

- Bookkeeping
  - Straightforward Within Cost Model
  - Can Adjust for Launch (Production) Rate, Cost Year, Learning Curve Effects

- All O&S Costs Will be Included in Cost Evaluation:
  - Technical Data Revisions
  - GSE Maintenance
  - Base Maintenance
  - Depot Maintenance
  - Spare and Repair Parts
  - Inventory Storage
  - Personnel Training
  - Logistics Down-time
  - Packaging and Preservation
  - Administration

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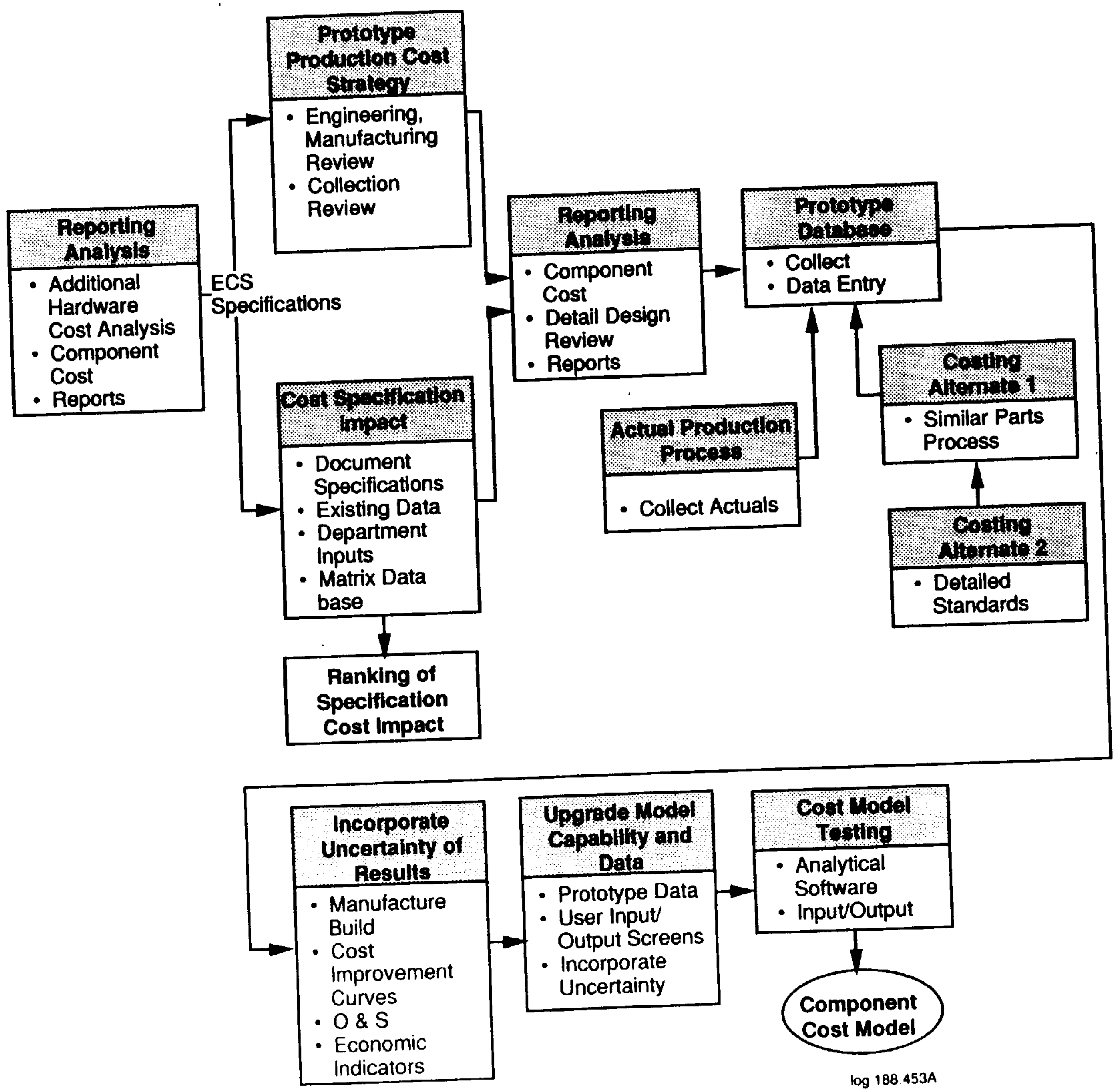
Phase II Cost Model Activities



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Concluding Remarks

Colin Faulkner

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We Have Back-ups for Identified Risks

Component	Risk	Alternatives
Impellers	Cast Titanium Ductility and Uniformity	Cast or Forged/Machined Shroud Attachment Technique
Turbine Housing	Adequate HEE Resistance in Cast Form	INCOLOY 909 Baseline and Stellite Back-up
Pump Housing	Cast Properties Inadequate at Cryogenic Temperatures	INCONEL 718 Baseline and Stainless Steel Back-up
Bearings	Insufficient Bearing Life	Improve Bearing Life by Evaluation and Testing of Promising Alternate Materials Two Bearing Designs Tested Hyrdrostatics Feasibility
Turbine Blade	Insufficient Damping	Tip Dampers Design Iterations and/or Tests
Balancing	Unbalance at Operating Speed Causes Reduced Bearing Life or Dynamic Instability	Early Analyses and Testing to Define Balancing Requirements
Performance Margin	Not Meeting Required Performance	Design Margin Against "Exhibit B" Requirements with Turbine Horsepower and Pump Discharge Pressure Margin.
Lift-Off Seals	Short Axial Length; Cocking	Two Interchangeable Concepts
Test Article	Damage in Transport and/or Test	Two Test Articles

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Program Status

- Critical "Long Leads" Started:
  - Impeller Castings (CAD Complete, Procurement Initiated)
  - Titanium Samples in Test Preparation
  - Procurement Initiated for Other Cast Test Bars
  - POD Concept Update Underway (Freeze in 3 Weeks)

- Planning Finalized for Rest of Phase I

M4D9/ALS H2 TPA/4

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Communications

- Interfaces Require Particular Consideration
- We Want to Benefit From SSME and ATP Experience
- We Want to Communicate as Closely as Possible With NASA
  — Disciplined System for Effective Follow-Ups

M4D9/ALS H2 TPA/3

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Report Documentation Page

1. Report No. DR-03	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle: ALS Liquid Hydrogen Turbopump Monthly Progress Report		5. Report Date: 21 July 1989
		6. Performing Organization Code
7. Author(s): Colin Faulkner, Program Manager; Nancy Shimp, Project Engineer; George Claffy, Project Engineer		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address: Aerojet TechSystems, P. O. Box 13222, Sacramento, CA 95813		11. Contract or Grant No.: NAS 8-37593
		13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration, Washington, DC 20546, NASA MSFC, Huntsville		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The monthly progress report provides visibility of significant technical and administrative activity occurring during the reporting period and work planned for next period.

17. Key Words (Suggested by Author(s)): Liquid Hydrogen Turbopump	18. Distribution Statement: Unclassified-Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	134	

NASA FORM 1626 OCT 86